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Soil, location, and climatic factors influencing available phosphorus level with depth in subsoil horizons of Iowa soils

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SOIL, LOCATION, AND CLIMATIC FACTORS INFLUENCING AVAILABLE PHOSPHORUS LEVEL WITH DEPTH IN SUBSOIL HORIZONS OF IOWA SOILS

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Soil, location, and climatic factors influencing available phosphorus level with depth in subsoil horizons of Iowa soils

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Hammed Mohammad Salih

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INTRODUCTION

Several researchers have shown that the distributions of available phosphorus (P) with depth in Iowa subsoils were influenced by several soil variables. Most of them, however, studied the effects of only one or two variables on subsoil P levels. From their research, the subsoil P distributions in most Iowa soils can be divided into two general patterns: (1) a sigmoid (S-shaped) curve, in which the P level decreases to a minimum below the plow layer (A3 to B1 horizons) and then increases with depth to a maximum in the deeper part of profile (lower B to upper C horizons), and (2) a decreasing curve, in which the subsoil P level is the maximum immediately below the plow layer and then decreases with profile depth.

In previous research on subsoil P levels, Salih (1979) studied the soil and location variables influencing the available P (Bray No. 1) in Iowa subsoils using multiple regression analysis. He included data from more than 700 profiles collected from all over Iowa. The analyses were restricted to the fixed depths of 30-51 cm (12-20 in.) and 76-107 cm (30-42 in.) in the soil profiles. Relationships between subsoil P and the variables frequently differed considerably in the shallow and deeper layers of the soil profiles.

To characterize the subsoil P distributions throughout the profiles mathematically, the depth variable was included in this study. The sigmoid subsoil P distributions in many soils indicated that the cubic function of the depth variable was necessary to explain these distributions. The large variability in the magnitudes of the P distributions with depth among soils also indicated that higher-order interactions involving depth and other variables should be included. The same data as used in the previous study were used to describe the subsoil P distributions from immediately below the plow layer to a depth of 127 cm (50 in.).

The location variables of S-N direction (legal township number, TWP) and the E-W direction (legal range number, RANGE) had significant effects on subsoil P levels in the previous study (Salih, 1979). The significant effects of location variables on subsoil P levels probably were indirect effects through their correlations with the climatic variables of annual precipitation and temperature. The climatic variables of mean annual precipitation (PPT), temperature (TEMP), and potential evapotranspiration (PE) have long been recognized as important variables influencing soil weathering and development and the distribution of available P with profile depth. The climatic variables, therefore, were included in this study to determine their effects on subsoil P distributions.

The objectives of this research were:

(1) To predict subsoil P levels at any depth in the soil profile from below the plow layer to 127 cm (50 in.) deep, utilizing depth, soil, location, and climatic variables;

(2) To predict subsoil P levels at any depth in the soil profile without the soil horizon variables whose estimation or determination is time consuming and costly;

(3) To compare the relative effects of the location variables

(TWP and RANGE) and the climatic variables (PPT, TEMP, and PE) for predicting subsoil P levels of Iowa soils; and

(4) To describe the methodology for studying the simultaneous effects of two or three variables and their many interactions, including the higher-order interactions with depth, on subsoil P distributions in Iowa soil profiles.

LITERATURE REVIEW

Phosphorus (P) is a very essential element in most life processes; it has been called "the key of life" because every living cell requires P as one of its components. Although P is considered to be immobile in soils, considerable redistribution can and does occur during the long time spans involved in soil profile development. The parent material is the only source of P in soils other than the minimal amount from precipitation and the amounts added in animal manure and fertilizers in recent years.

Intensive studies of P in the soil surface horizon including its chemical reactions with soil particles, methods of extraction, and availability to plants have been conducted by many researchers. Much more is known about amounts and behavior of P in the surface soil than in the subsoil. Thus, there is an essential need for more knowledge about subsoil P, its distribution in the soil profile with depth, its availability, and its contribution to the P requirements of plants. This can be achieved by learning more about the soil, location, and climatic variables that affect the available P status in the soil profile.

Because this study focused on factors affecting subsoil P levels in Iowa soils, previous studies in Iowa on subsoil P levels and factors influencing the distribution of P with profile depth will be reviewed briefly.

Distribution of P with Profile Depth in Iowa Soils

Several investigators have studied the distributions of extractable P in Iowa soils (Pearson et al., 1940; Godfrey and Riecken, 1954, 1957;

Mausbach, 1969; Tembhare, 1973; Birchett, 1974). Their results and those of others (Drs. L. C. Dumenil, T. E. Fenton, and F. F. Riecken, Department of Agronomy, Iowa State University, unpublished data) have been reviewed in detail by Salih (1979).

In general, their studies showed that the subsoil P distributions throughout the profile depth in most soils can be divided into two patterns: (1) a sigmoid (S-shaped) curve, in which the P level decreases to a minimum below the plow layer (A3 to B1 horizons) and then increases with depth to a maximum in the deeper part of the profile (lower B to upper C horizons), and (2) a decreasing curve in which the subsoil P level is the maximum immediately below the plow layer and then decreases with profile depth. In some soils derived from till and soils with a calcareous horizon in the midpart to deeper part of the profile, the sigmoid distribution occurs in the upper half to two-thirds of the profile. Below the maximum P zone in these soils, the subsoil P level decreases sharply and frequently becomes less than the minimum P level in the upper profile.

Influence of Weathering and Profile Development on Inorganic P and its Availability to Plants

The relative quantities of inorganic P (Ca-P, Al-P, and Fe-P) have been utilized in several studies as indicators of weathering and profile development (Godfrey and Riecken, 1954, 1957; Bauwin and Tyner, 1957; Chang and Jackson, 1958; Hsu and Jackson, 1960; Chang and Juo, 1963; Hawkins and Kunze, 1965; Mausbach, 1969; Smeck and Runge, 1971; Smeck, 1973). They generally agreed that the dominant inorganic P forms resulting from the least weathering to the strongest weathering were: calcium phosphate - aluminum phosphate - iron phosphate - occluded phosphate. Many of these studies were discussed in more detail by Salih (1979).

A number of researchers have correlated P availability as determined by chemical tests to the different P fractions. Hawkins and Kunze (1965) found a significant correlation between available P and Al-P in Texas Grumusols. Williams and Walker (1969) reported that, as the weathering degree of the profile increased, the acid extractable Ca-P declined to zero and NH_4F-P increased to maximum values and then declined. Smeck and Runge (1971) reported a progressive increase in P availability in profiles along a traverse from Haplaquolls toward the Albaqualf end of the transect. The P availability tended to increase as the degree of profile development increased.

Many methods developed for obtaining indexes of P availability of soils have involved extraction of the soil with inorganic acids, organic acids, dilute alkaline solutions, and buffered salt solutions. The common laboratory extraction methods are Bray No. 1 and Bray No. 2 (Bray and Kurtz, 1945) and the Olsen method (Olsen et al., 1954). These methods were discussed in detail by Tembhare (1973) and Birchett (1974). The chemical method used must be considered as an important factor affecting extractable P levels; this factor was reviewed by Salih (1979).

Soil Variables Affecting Subsoil P Levels

Many investigators have related subsoil P levels to different soil variables. Most of them, however, have studied only the effects of one variable or of a few variables on subsoil P levels. In these studies, it was difficult to assess the direct and indirect effects of the soil variables on subsoil P. Henao (1976), Pena-Olvera (1979), and Salih (1979) reported a varying degree of intercorrelation among soil variables, particularly within related groups of variables such as the organic matter, texture, and soil pH groups. Salih (1979) also found that many interactions occurred between soil variables in their effects on subsoil P levels.

In his multiple regression analyses of subsoil P (Bray-1) levels in two fixed index layers in the profile on soil variables, Salih (1979) grouped them into horizon, parent material, profile, and location variables. Horizon variables included those with specific values for each genetic horizon sampled from the soil profile, such as soil pH, soil test K level, clay content, organic carbon, and bulk density. Parent materials were grouped into deep loess, till and paleosol, colluvium in loess areas, alluvium in loess areas, alluvium in till areas, eolian sands, and shallow loess (51-102 cm) over till. The profile variables included those having one value for the profile, such as slope, slope configuration, erosion class, thickness of A horizon, drainage class, biosequence, minimum pH in the profile, depth to minimum pH, depth to carbonate (calcareous) layer, and depth to maximum clay horizon. The location of the profile in the state was described by the legal range number (E-W direction) and legal township number (S-N direction).

Salih (1979) found that the profile variables were the most important for predicting subsoil P in both the upper (30-51 cm) and lower (76-107 cm) layers of the profiles. The parent material variables were slightly more important than the horizon variables for predicting subsoil P in the upper layer but their importance was reversed in the lower layer. The location variables, related to climatic differences in Iowa, had the least effect on subsoil P but had significant effects in all models. The effects of the soil variables on subsoil P levels will be discussed in the following sections.

<u>Horizon variables</u>

<u>Soil pH</u> Hsu and Jackson (1960) found that the transformation of soil P from the Ca-P form to the more extractable and available Al-P and Fe-P forms in the B and C horizons was controlled mainly by decreasing soil pH, which reflected weathering, leaching, and soil development.

Salih (1979) found that soil pH had a highly significant, negative, linear effect on soil test P in the deep 76-107 cm (30-42 in.) layer; its effect was modified by interactions with organic carbon, several of the parent material variables, township (S-N location), and biosequence. Soil pH also had a significant effect on soil test P in the shallow 30-51 cm (12-20 in.) layer but was not included in final models because the highly correlated depth to carbonate layer variable had a greater effect on soil test P.

<u>Genetic horizon</u> The influence of weathering on soil development and inorganic P compounds (discussed previously) not only affects

extractable-P distributions but also soil pH and clay distributions in relation to genetic soil horizons. The minimum subsoil P level has occurred in the lower A to upper B horizon and the maximum level has generally occurred in the lower B or upper C horizon (Pearson et al., 1940; Mausbach, 1969; Tembhare, 1973; Birchett, 1974).

Salih (1979) found that the soil test P level in the shallow 30-51 cm layer was significantly affected by the genetic horizon present in that layer; this effect was modified by interactions with other variables. In the regressions involving soil test P in the deeper 76-107 cm layer, the genetic horizon variable was deleted because of its high correlations with soil pH ($r = 0.71$) and depth to carbonate horizon ($r = -0.82$).

<u>Soil test K in the subsoil</u> Salih (1979) found that the soil test K level had significant effects on the subsoil P levels in both the shallow and deep layers of the profile. Its effects on subsoil P were modified by interactions with clay content, drainage class, township location, and biosequence. The relationship between soil test K and subsoil P probably reflects the indirect effects of other variables such as E-W location, erosion, and drainage which affect both.

<u>Clay content</u> Tembhare (1973) reported that, in general, although a few exceptions exist, the higher the B/A clay ratio, the higher the average available P content of the soil. He also stated that the relationship between the B/A clay ratio and the available P content seems to be confounded with other soil factors and soil properties.

Salih (1979) found that the clay content had a significant, positive, linear effect on soil test P in the 30-51 cm (12-20 in.) layer, modified by interactions with soil test K, bulk density, township, thickness of A horizon, and drainage. He also found that clay content had a curvilinear effect on soil test P in the 76-107 cm (30-42 in.) layer, modified by an interaction with biosequence. Maximum subsoil P occurred at clay contents of 24-31%.

The other textural components (sand and silt) had slight effects on subsoil P in the absence of the clay variable but none in its presence (Salih, 1979).

Organic carbon Smeck (1973) reported that the P content of the soil is a major factor governing accumulation of organic matter; soils high in P will contain higher levels of organic matter than soils low in P. Thus, the organic carbon content should be related to the subsoil P level.

Salih (1979) found that the organic carbon level had a significant effect on subsoil P of the 76-107 cm layer; its effect was modified by interactions with pH, S-N direction, slope, and biosequence. The organic carbon level did not have a significant effect on subsoil P in the 30-51 cm layer because the highly correlated slope ($r = -0.55$) and thickness of A horizon ($r = -.81$) variables had greater effects.

Bulk density Salih (1979) found that bulk density had a significant effect on subsoil P in the shallow 30-51 cm layer, modified by several interactions. Its effect was primarily indirect through its correlation with till parent materials ($r = 0.70$). The till parent material had a more dominant effect than bulk density ($r = 0.79$) on subsoil

P in the deep 76-107 cm layer.

Parent material variables Several researchers reported that the loess-derived soils contained higher total P and plant-available P in their profiles than the till-derived soils (Pearson et al., 1940; Mausbach, 1969; Tembhare, 1973). Dumenil (1978) reported that subsoil P levels varied among the soils derived from deep loess, till, colluvium, and alluvium in southwestern and southern Iowa.

Salih (1979) found that each of the groups of soils derived from till, colluvium below loess, alluvium in loess areas, alluvium in till areas, eolian sands, and shallow loess over till had significantly different levels of soil test P in both the shallow (30-51 cm) and deep (76-107 cm) soil layers compared with the average of all other soils dominated by the soils derived from deep loess. The effects of all parent material groups on soil test P were modified by one or more interactions with other soil variables, particularly the biosequence variable.

Profile variables

Slope, erosion class, and thickness of A horizon Several investigators have studied the effects of slope, erosion class, and thickness of A horizon on subsoil P levels (Tembhare, 1973; Birchett, 1974; Dumenil, 1978). Salih (1979) has reviewed most of this research in detail; the Bray-1 subsoil P levels decreased with increasing slope, increasing erosion, and decreasing thickness of A horizon. He also reported that these variables along with other organic matter related variables of organic carbon and slope configuration on the landscape were all highly intercorrelated. The simple correlations between these variables varied from 0.6 to 0.8.

In his regression models, Salih (1979) found that slope and thickness of A horizon had larger effects on subsoil P levels than the correlated erosion class and slope configuration variables. The effects of both slope and thickness of A horizon on subsoil P in the upper and lower profiles were modified by interactions with other variables including clay, township (S-N location), drainage, and biosequence.

Drainage class Several investigators, including Bauwin and Tyner (1957) and Runge and Riecken (1966), have reported that total P and available P in subsoils were lower in the poorly-drained soils than in the somewhat poorly-drained and well-drained soils. Mausbach (1969) found that the subsoils of the poorly-drained soils had more Ca-P and less sesquioxide-P than the associated better drained soils. The drainage effect on subsoil P may be confounded with the higher pH in the poorly-drained soils.

Salih (1979) found that drainage class had significant effects on soil test P in both the upper and lower layers of the soil profile. Its effects were modified by many interactions with other variables but most frequently with range (E-W distance) and biosequence. The minimum soil test P levels in both layers were associated with somewhat poor to poor drainage.

Biosequence Many investigators have reported that biosequence (prairie to transition to forest) had a dominant effect on soil test P in the subsoil (Pearson et al., 1940; Fenton et al., 1967; Mausbach, 1969; Tembhare, 1973; Birchett, 1974). The forest-derived soils had higher subsoil P levels and more marked sigmoid distributions with depth than the prairie soils. The transition soils had intermediate levels.

Salih (1979) found that biosequence had a curvilinear effect on soil test P in the upper layer but a linear effect on soil test P in the deeper layer. Minimum soil test P levels occurred in the prairie soils of the biosequence. The effect of biosequence on subsoil P was modified by interactions with many variables which included most of the horizon, parent material, and other profile variables.

Other profile variables Several profile variables which reflect the degree of weathering or soil development include minimum pH in the profile, depth to the midpoint of the minimum pH horizon, depth to the top of the carbonate or calcareous horizon, maximum clay in the profile, and depth to the midpoint of the maximum clay horizon. The effects of weathering on the subsoil P levels and on these variables have been discussed previously.

Salih (1979) found that the depth to minimum pH had a significant linear effect on soil test P in the upper layer modified by interactions with till-derived soils, alluvium-derived soils in loess areas, and depth to maximum clay layer. In the deeper 76-107 cm layer, depth to minimum pH had a significant curvilinear effect on soil test P modified by interactions with till-derived soils and alluvium-derived soils in till areas.

Several researchers have correlated amounts of Ca-P with the extractable P by the Olsen and Bray-1 methods (Chai and Caldwell, 1959;

Susuki et al., 1963; Pratt and Garber, 1964; Mausbach, 1969; Tripathi et al., 1970). They found that amounts extracted by both methods were not significantly correlated with Ca-P fractions in the soil. However, amounts of P extracted by chemical methods and plants from calcareous horizons containing mostly Ca-P are very low, particularly in the subsoil horizons (Tembhare, 1973; Birchett, 1974). They found that amounts extracted by the Bray-1 method were not as well-correlated with plant-extractable P as were the amounts by the Olsen method in these calcareous horizons.

Salih (1979) found that the depth to carbonates in the profile had significant and generally linear effects on soil test P levels in both the 30-51 cm and 76-107 cm layers; these effects were modified by interactions with several other soil and parent material variables.

The depth to clay maximum variable had a linear effect on subsoil P in the upper profile and a curvilinear effect on subsoil P in the lower profile (Salih, 1979). Its effects were also modified by several interactions.

Salih (1979) did not include maximum clay in the profile as a variable in his regressions. To estimate the effect of maximum clay on subsoil P in the 76-107 cm (lower profile) layers, he included a soil permeability class variable which was very highly correlated with maximum clay ($r = 0.93$). In the absence of the horizon variable of percent clay, the effects of permeability class on subsoil P indicated that maximum clay would have a significant effect on subsoil P, primarily through its interactions with biosequence and depth to carbonates.

<u>Location variables</u>

If soil parameters show a systematic change directionally across an area such as Iowa, this directional effect should be accounted for in prediction equations. The location variables may be useful although their effects on a soil parameter such as subsoil P may be indirect through their relationships with causative factors. For studies in Iowa and central U.S., it is convenient to use the legal township and range numbers to describe the S-N and E-W directional effects, respectively. These can be used to locate the soil profile within a 6 by 6 mile square area.

Jenny and Leonard (1934) showed the soil pH decreased and depth to carbonates increased along a W-E traverse from eastern Colorado into eastern Missouri. They related these directional effects to increasing rainfall. Hutton (1948) and Ulrich (1949) studied the sequence of Iowa prairie soils along a traverse from southwestern to southeastern Iowa. They reported that subsoil pH decreased and depth to carbonates increased from west to east. These effects along with effects on other soil parameters were related to an increase in climate-related leaching and weathering. Protz and Riecken (1968) and Wells and Riecken (1969) also showed a relationship between increasing acidity, west to east direction, and increasing rainfall.

Salih (1979) included the location or directional variables in his regressions of subsoil P on soil variables. Both township (S-N direction) and range (E-W direction) had significant linear effects on subsoil P in both the upper and lower profiles. The effect of township was modified by more interactions than that of range. The interactions between township and thickness of A horizon and between range and drainage class occurred consistently in all models. These effects of the location variables on subsoil P were attributed primarily to the effects of the climatic variables of rainfall and temperature although they may be also related to the distribution of different parent materials and soil associations in Iowa.

Depth in the profile

Many researchers have shown graphically the distributions of extractable P in Iowa soil profiles, but no one has described these distributions mathematically (Pearson et al., 1940; Godfrey and Riecken, 1954, 1957; Mausbach, 1969; Tembhare, 1973; Birchett, 1974; Drs. L. C. Dumenil, T. E. Fenton, and F. F. Riecken, Department of Agronomy, Iowa State University, unpublished data). Their studies showed that the subsoil P distributions in most soil profiles had two general patterns with increasing depth: (1) a sigmoid (S-shaped) curve, and (2) a decreasing curve, both of which were discussed in a previous section. The minimum and maximum subsoil P levels and depths to minimum and maximum subsoil P levels, however, varied widely among the many soil series and mapping units in Iowa.

To describe the subsoil P distributions in soil profiles mathematically, it is obvious that depth in the profile is a very important variable. In the initial phases of this study, Salih (1979) eliminated the depth variable by investigating the variables influencing subsoil P levels in fixed index layers 30-51 cm (12-20 in.) and 76-107 cm (30-42 in.) deep. The different effects of the variables and different mix of interaction variates in the regression equations for the two layers indicated that the effect of depth on subsoil P level would be modified by many interactions between depth and the other variables.

No reference in the literature was found in which the distribution of a soil parameter in soil profiles was regressed on depth and other variables and the interactions involving the depth variable. Dumenil (Dr. L. C. Dumenil, Agronomy Department, Iowa State University, unpublished data), however, regressed the organic carbon content of subsoil horizons from 750 soil profiles on the Munsell color components (hue, value, and chroma) of moist soil, location within the state and on the landscape, horizon depth, soil texture components, slope, erosion class, drainage class, biosequence, and previous land use (cultivated or noncultivated). The final multiple regression model had 40 variates and an R^2 of 0.88 (Henao, 1976). In this equation, the effect of depth on organic carbon was modified by significant interactions with silt, clay, biosequence, bottomland, cultivation, and the color components of value and chroma. This multiple regression prediction equation thus showed that the organic carbon level of any horizon in a wide range of soil profiles could be predicted by including the quadratic function of the depth variable and several significant interactions between horizon depth and other variables.

Because the objective of the present study was to develop multiple regression equations to predict the subsoil (Bray-1) distributions for a wide range of soil, location, and climatic variables, the depth variable had to be included. The sigmoid distribution in many profiles also indicated that a cubic function of the depth variable was needed. The wide variations in subsoil P levels with depth indicated that many linear*linear interactions between depth and other variables should be tested. The variation in the minimum and maximum subsoil P levels and depths to the minima and maxima in the profiles with sigmoid distributions of subsoil P also indicated that depth was involved in complex interactions between the quadratic and even the cubic functions of depth and other variables.

Climatic Variables Affecting Subsoil P Levels

As discussed previously, Salih (1979) found that the location variables of township number (S-N direction) and range number (E-W direction) had significant effects on subsoil P modified by several interactions with other variables. He attributed these effects primarily to the climatic variables of rainfall and temperature.

These directional variables (or any other directional variables) are useful in regression analyses if rainfall and temperature vary generally in these directions, as they do in Iowa. These variables may not be useful, however, in other areas of the United States or the world if there is little relationship between direction and the climatic variables. Directional variables may be even less useful in areas where a third dimension (altitude) is also related to the climatic change.

To determine if climatic variables are as useful as the location (directional) variables for explaining variations in subsoil P among soils, climatic variables were included and tested in this study.

Jenny (1941) postulated that the independent soil forming factors of climate, organisms, topography, parent material, and time completely describe the soil system; i.e., for given levels of any combination of these factors, only one soil type exists. The important climatic variables were moisture factors of rainfall and evapotranspiration and the temperature factor. Although many combinations of mean monthly, seasonal, and annual values of the climatic variables can be used, Jenny (1941) stated that, as long as the soil-climate functions are studied within regions of uniform seasonal distributions, the mean annual rainfall and temperature values give satisfactory correlations. Although the soil temperature regulates the chemical reaction rate in the soil, he stated that the readily-available air temperatures are functionally interrelated with soil temperature.

The Soil Survey Staff (1975) refers to the soil moisture and soil temperature regimes as important properties of the soil as well as determinants of processes that occur in the soil. The soil moisture regime is only a partial function of climate, however, because other factors influence the relationship between soil moisture and rainfall and evapotranspiration. Each moisture regime in the history of a soil is a factor in its genesis, but the present moisture regime of most soils is determined by the present climate. A number of methods have been used to relate soil moisture to meteorological records but all have some shortcomings. The mean annual soil temperature is most closely related to mean annual air temperature.

To illustrate the soil moisture and temperature regimes by graphs that accompanied descriptions and data for soil pedons, the Soil Survey Staff (1975) used the average monthly values for precipitation, temperature, and potential evapotranspiration. However, they noted that these give an oversimplified picture of the soil moisture regime. They used the monthly climatological standard normal (1931-60) values of temperature and precipitation and the monthly potential evapotranspiration (PE) normals from the Thornthwaite collection (Mather, 1964, 1965).

Ruhe (1969) summarized the climatic changes in Iowa over time based on radiocarbon chronology and pollen studies. Conifers decreased about 10,000 years ago. Deciduous trees became dominant and then waned 6000 to 7000 years ago. Nonarboreal species (grasses, sedges, weeds, etc.) increased 7000-8000 years ago, became dominant 5400-6600 years ago, and have remained dominant to present. He associated the changes in plant species to climatic changes from the cool, relatively moist, postglacial period followed by a warming trend to the present warmer and drier period with its prairie vegetation. He also stated that the soil formation on hillslopes occurred in the last 7500 years and on summits since 14,000 years ago.

The climatic variables influencing the genesis and morphology of soil profiles in Iowa during all or most of their development thus should be similar to and highly correlated with their recent mean annual values. The effects of these variables on soil parameters will be discussed in the following sections.

Precipitation

Thorp (1931) concluded that as the rainfall increased, the depth to the horizon of lime accumulation increased. He also stated that the thickness of the heavy subsoil or upper B horizon increased with an increase in rainfall.

Jenny and Leonard (1934), who studied changes in soil properties along a W-E transect in central United States, stated that increasing moisture was responsible for the higher clay and colloid content of soils because of intensified weathering. They also stated that soils were alkaline in the semi-arid region, whereas an acid reaction was characteristic in the humid districts. As a first approximation, they said that an increase of one inch of mean rainfall reduced the average pH by one-tenth; the soil pH of the surface soil changed from 7.8 in the semi-arid region to 5.2 in the semi-humid area. They found that soil N also increased continuously with increasing rainfall.

Jenny (1941) extensively reviewed the literature dealing with climate as a soil-forming factor. He also derived simple mathematical functions to relate soil parameters to rainfall and temperature variables. His main conclusions about the effects of rainfall were as follows: (1) the N and organic matter content of surface soils and of subsoils to a lesser degree became higher as moisture increased; this relationship was more pronounced for prairie than for forest soils; (2) as rate of leaching increased with increasing rainfall, the depth to the carbonate layer increased and the soil pH progressively decreased throughout the soil profile; (3) as rainfall increased, weathering increased and colloidal clay content increased; the colloidal clay particles control to a great extent the physical and chemical behavior of soils; (4) with increased colloidal clay content associated with increased rainfall up to about 26 inches of annual rainfall, the exchange capacity of soils increased and total exchangeable bases increased; as rainfall further increased, the relationships among cations changed as exchangeable bases decreased and acidic cations of H and Al increased on the exchange complex; and (5) as rainfall became greater and weathering and clay formation increased, soil aggregation increased, particularly in the presence of high organic matter levels.

The soil property - moisture functions evaluated by Jenny (1941) were mainly of linear, logarithmic, or exponential forms. He stated that over a wider moisture range, the curves are of the sigmoid type. He also stated that the influence of rainfall on soil development was not the same for all constituents involved in the process. The H^+ concentration and depth to carbonate horizon reacted most sensitively to rainfall variations; N and organic matter were less sensitive, and clay and saturation capacity were still less sensitive to rainfall variations. Because Salih (1979) found that many of the variables related to organic matter, clay, and soil pH levels had significant effects on subsoil P levels, one can infer that the moisture variables of rainfall and potential evapotranspiration will also influence subsoil P levels either directly or indirectly through other soil parameters.

More recently, several researchers concluded that the leached soils accumulated greater P in the B horizons of the profile (Allaway and

Rhoades, 1951; Smeck and Runge, 1971; Smeck, 1973). Walker (1965) and Smeck (1973) reported that as annual rainfall increased above certain levels the amounts of extractable P decreased and the occluded P increased; the latter thus can be used as an indicator of soil age and climatic regime.

According to Walker and Adams (1958) and Hinkley et al. (1970), the content of soil P is a major factor controlling the distribution of vegetation types and accumulation of organic matter.

Temperature

Jenny (1935) related the clay content of profiles developed from crystalline rocks in the eastern United States to climatic factors. He found that the average clay content increased from north to south. He stated that temperature and rainfall to a lesser degree were responsible for the high clay levels in the soils of the south.

Jenny (1941) also reviewed the literature relating the effects of temperature on soil development and soil variables. Significant correlations between soil properties and mean annual temperatures were obtained, provided other soil-forming factors including moisture were held constant. He stated that weathering in tropical regions proceeds three times faster than in temperate zones and nine times faster than in the Arctic. He also noted that early soil scientists observed that depth of weathering increased, soil colors changed from gray, black, or brown to yellow and dark red, and leaching of bases increased as temperatures increased.

Jenny (1941) summarized the effects of temperature on soil N and organic matter as follows: (1) within belts of uniform moisture condition and vegetation, the average contents of both decrease exponentially as the annual temperature rises; (2) for each decrease of 10°C in annual temperature, the average N and organic matter contents of the surface soil increase from 2 to 3 times provided the annual precipitation - evapotranspiration ratio is kept constant; and (3) in warm climates, decomposition of organic matter is accelerated but in cool regions, accumulation is favored.

He also stated that the clay content of soils increased exponentially as temperature increased and that all soil variables related to clay content were influenced by temperature. In all of these relationships, the influence of climate on soil formation is complicated by the interactions between moisture and temperature. He acknowledged that it is difficult to determine the individual effects of rainfall and temperature over wide ranges on soil variables although the combined effect may be very marked.

The conclusion can be drawn that temperature will influence subsoil P distributions in soil profiles since it influences many of the soil variables that have significant effects on subsoil P levels (Salih, 1979).

Potential evapotranspiration

Jenny (1941) cited several early researchers who had used precipitation-evaporation ratios as a basis for climate classification. He explained that the main advantage of a precipitation-evaporation ratio map over a rainfall map was for comparing soil moisture conditions of regions having similar rainfall but different temperatures and air humidities.

Thornthwaite (1931) first proposed a moisture classification which he called a precipitation effectiveness index to account for evapotranspiration effects. This index was a summation over 12 months of a function based on monthly precipitation divided by monthly temperature.

Later, Thornthwaite (1948) developed his potential evapotranspiration (PE) index which has been widely used to the present time. He had found that, when adjustments were made for variations in day length, there was a close relationship between mean monthly temperature and potential evapotranspiration. He described the three steps that were involved in the compilation of the PE index based on mean monthly temperatures and the latitude of the weather station. All three steps were accomplished by use of a nomogram and tables. Straight lines on the nomogram defined the linear relationships between the logarithms of temperature and unadjusted PE. The final PE values were adjusted for day and month length.

Thornthwaite (1948) also explained how numerical values of water surplus and water deficiency could be obtained by treating precipitation as income, potential evapotranspiration as outgo, and soil moisture as a reserve that may be drawn upon as long as it lasts. The monthly PE normals from the large Thornthwaite collection for many of the weather stations in the United States were listed by Mather (1964, 1965).

The Soil Survey Staff (1975) used mean monthly precipitation, temperature, and PE to describe the soil water balance of the soil. On the graph of these values for the 12 monthly periods, the periods of surplus, utilization of the <15 bar water, deficit (before recharge begins), and recharge of the plant available water capacity were shown for soils developed under different climatic conditions. They stated that the moisture regime of the soil is an important property of the soil as well as a determinant of the soil development processes.

MATERIALS AND METHODS

General Description

The soil test data used for this study came from two sources: (1) 663 profiles sampled for a long-term soil productivity project; and (2) 33 profiles sampled by the Soil Survey Group of the Agronomy Department, Iowa State University.

The 663 soil profiles were collected under the supervision of Drs. F. F. Riecken and L. C. Dumenil of the Agronomy Department for the Iowa Agriculture and Home Economics Experiment Station Project 1377 (revised projects 1958 and 2326 in 1972 and 1978, respectively) with the cooperation of the Iowa Cooperative Extension Service, the Soil Conservation Service, USDA, and many farmer-cooperators. The title of the project was "Crop yielding capacity of Iowa soil types under different soil, management, and fertility levels."

The project was initiated in 1957 in two counties and counties were added each year until 1962 when the fifteenth county was added. These counties (the ones with the large number of profiles) are shown in Figure 1. The 15 counties were selected to represent major soil association areas in the state, all of which were represented except the Adair-Grundy-Haig area in southern Iowa. The selection of the sites within the counties was described by Henao (1976) and Salih (1979).

The 33 profiles sampled by the Soil Survey Group were used because laboratory data were available. These profiles were modal series sites or from slope traverses in selected areas. The laboratory data from all horizons and soil profile descriptions for these are listed in Soil

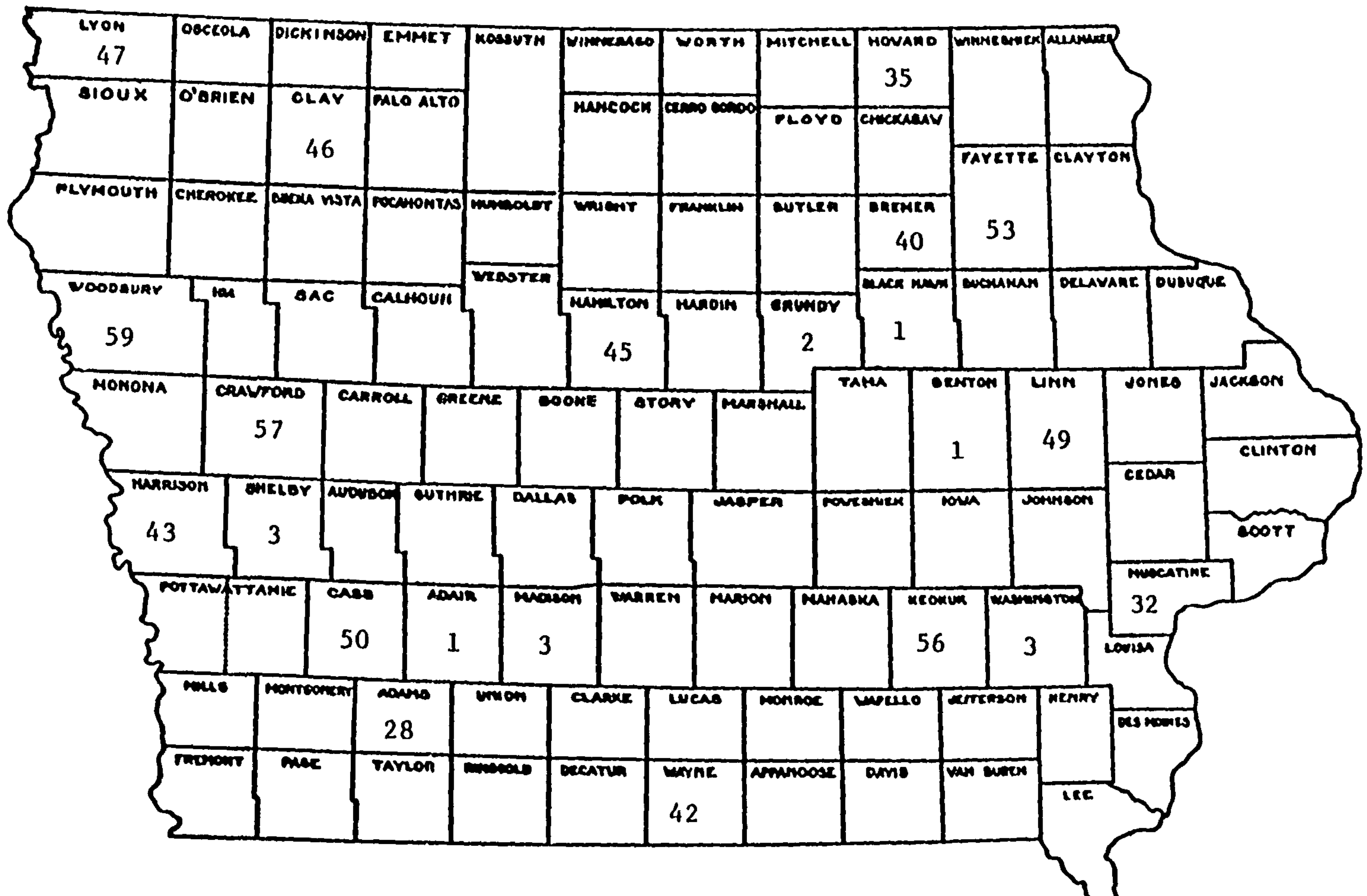

Figure 1. Location and number of soil profiles in the various counties used for this study

Conservation Service, USDA (1966, 1978). Number of profiles from Cass, Wayne, Keokuk, and Bremer counties were 4, 6, 3, and 6, respectively. Locations of the other profiles are shown in Figure 1.

In the initial study of available P levels in Iowa subsoils, Salih (1979) included a total of 720 profiles. For this study 696 profiles were included in the analyses. Most of the profiles deleted were those that had 30 cm (12 in.) or more of overwash materials; presence of these materials changed the P distributions with depth which could not be accounted for with the variables used. A few others were deleted because of manure influence (former feed lots, barnyards, or haystack bottoms) which increased subsoil nutrient levels markedly.

Soil scientists of the Soil Conservation Service and/or Agronomy Department personnel located the sites, described the soil profiles by horizons to a depth of 100-150 cm (40-60 in.), and collected soil samples by genetic horizons for later analyses. Characteristics recorded at the time the site was located and described included: horizon differentiation and boundary description; texture, color, structure, mottlings, consistence, and pH of each horizon; parent material; drainage class; biosequence; slope, configuration and aspect; erosion class; miscellaneous features of the profile; and soil unit number and soil type (Henao, 1976).

From each of the 663 profiles sampled for the soil productivity study, 4 to 10 horizons were sampled. Each horizon of each profile was tested for pH and available N, P, and K by the Iowa State University Soil Testing Laboratory. The methods used for obtaining or estimating the horizon, parent material, location, and profile variables were described in detail by Henao (1976). The modifications of some of the variables were described by Salih (1979). The variables used for this study will be discussed briefly in the following sections. The data listing sheets for the coding and identification of these variables on the original punched computer cards are given in Appendix Tables A1 and A2.

Depth in the Profile

In the initial study of subsoil P levels, Salih (1979) regressed the subsoil P levels of the fixed-depth index layers of 30-51 cm (12-20 in.) and 76-107 cm (30-42 in.) on the horizon, parent material, location, and soil profile variables. These index layers were selected because the minimum and maximum soil test P levels of most soils occur in these layers. The soil test P level in the deeper layer has been used to characterize differences among soils and as a variable in corn yield regressions.

The major objective of this study was to predict mathematically the soil test P distributions as functions of depth and many other variables by utilizing data from all subsoil horizons in the profile. Depth to the midpoint of the sampled horizon (symbol - DEPTH) therefore became an important variable in the regression analyses. The decreasing and sigmoid (S-shaped) subsoil P distributions with depth described by Salih (1979) implied that these distributions will be linear, quadratic, or cubic functions of DEPTH, depending on several factors. The DEPTH was originally listed in inches to the midpoint of each sampled horizon and then it was transformed to cm. Later, DEPTH was transformed to meters for the regressions involving interactions with $DEPTH^2$ and $DEPTH^3$ to avoid the very large values of $DEPTH^3$ and resulting very small regression coefficients.

Soil Horizon Variables

Several variables were used to express the variations of soil parameters among soil horizons with depth. These soil horizon variables were deleted as a group in some regression models to determine how well subsoil P levels could be predicted from the parent material, location, soil profile, and climatic variables. The horizon variables are the most costly and time-consuming to determine or estimate accurately. The other variables can be determined easily from the soil profile descriptions, location of the profile, and isoline maps of climatic averages.

Soil test variables

Soil samples from all profiles used in this study were collected from each horizon at the time the profile was described. They were kept refrigerated in the field-moist condition in air-tight bags and later analyzed for soil pH, buffer pH, nitrifiable N, available P, and exchangeable K by the Iowa State University Soil Testing Laboratory. The testing procedures used and the modifications in the procedures in 1963 were described in detail by Henao (1976) and Salih (1979).

The soil test variables of each subsoil horizon included in this study were pH determined in a 2:1 water-soil ratio on an air-dried sample, available P determined by the Bray No. 1 method on a field-moist sample, and exchangeable K on a field-moist sample. The symbols for these variables are PH, STP, and STK, respectively. PH was expressed as pH units initially and then was coded by subtracting the minimum observed value of 4.5 from all values. STP and STK values were expressed as pp2m of P and K.

Soil texture

Mechanical analyses of all or selected horizons were run on about 10% of the profiles from the soil productivity study and on all 33 profiles sampled by the Soil Survey Group. For all others, the percentage clay (<0.002 mm) and percentage sand (>0.05 mm) fractions of each horizon of each profile were estimated by Dr. T. E. Fenton, Agronomy Department for Henao (1976). These estimates were based on the texture of each horizon estimated by the one who described the soil profile and on many previous mechanical analyses of the textural components from the same or similar soil types. The symbols for the textural variables are SAND, SILT, and CLAY.

Organic carbon

The percentage of organic carbon (OC) in each of the described soil horizons to a depth of 50-76 cm (20-30 in.) was determined for 108 of the 663 soil productivity study profiles; the profiles analyzed were the more eroded, forested, and sandy soils. These data along with data from 605 other profiles were used to derive a multiple regression equation for the OC level of each described horizon on the Munsell color components (hue, value, and chroma) of moist soil, location within the state and on the landscape, horizon depth, soil texture components, slope, erosion class, drainage class, biosequence, and previous land use, cultivated or uncultivated (Henao, 1976).

The complete regression model for the OC of the subsurface horizons included 3202 observations and 74 variates and had an R^2 of 0.882. The reduced regression equation used for predicting the OC of the subsurface horizons had 40 variates and an R^2 of 0.879 and is listed in Henao (1976). The OC values for each of the horizons of the Project 1377 soil profiles to the depth where the OC was certain to be less than 0.5% were then estimated from this regression equation by Henao (1976). For this study, the OC values for horizons deeper than those estimated previously were estimated by Salih (1979) from similar soils which had been analyzed to a depth of 125 cm (50 in.) or greater.

Bulk density

The bulk density values (BD) of all horizons of the soil productivity study profiles were estimated as described by Henao (1976). The bulk density distributions with depth were estimated from all available Iowa data and graphed for the major soil types. Bulk densities of related soils were estimated from the curves for the major soils with the advice of Dr. T. E. Fenton, Agronomy Department. All of the curves and adjustments were shown by Dumenil (1978). The BD values in g/cm^3 were coded by subtracting 1.00 and then multiplying by 100 to reduce the correlations between the linear, squared, and interaction bulk density variates.

<u>Genetic horizon</u>

The genetic horizon for each horizon of the profile was designated by the Soil Scientist in the profile description. To include the genetic horizon as a parameter to estimate the degree of weathering within the profile, the coding of the genetic horizons was based on the Bray-1 levels of horizons in the deep loess soils sampled by Birchett (1974). The genetic horizons were coded by Salih (1979) to give an approximate linear relationship between subsoil P values and genetic horizons, as follows:

A1, A2, A3 or B1 = 20	B3 or B32 = 70
B21 = 30	C1 = 80
B2 or B22 = 40	Cca = 00 for STP regressions
B23 = 50	Cca = 80 for STK regressions
B31 = 60	

The symbols used for the genetic horizon variable were GHP and GHK for STP and STK regressions, respectively.

The genetic horizon variable was considered as a soil horizon variable in some regression models. For other regression models, genetic horizon was grouped with the soil profile variables because it could be determined from the soil profile description.

Parent Material Variables

The soil parent material of each horizon in the profiles was characterized by using dummy variables (0 or 1 entries) in columns 43 to 53 of the computer data cards as listed in Appendix Table A1.

The parent material groups with some examples were as follows:

(1) Oxidized loess—most common of the parent materials in Iowa and occurring in all horizons of most well- to moderately

well-drained deep loess soils (Monona, Marshall, Sharpsburg, Moody, Galva, Otley, Tama, Fayette, etc.) and the associated somewhat poorly drained soils (Macksburg, Primghar, Mahaska, Muscatine, Stronghurst, etc.).

(2) Deoxidized loess--horizons having a gray 10YR 5/2 or 6/2 matrix color occurring at the surface (Dow), at a shallow to moderately shallow depth in some moderately well-drained soils (Nira and Hedrick) and in some poorly drained soils (Marcus, Taintor, and Garwin), and in the deepest horizons of some of the deep loess soils mentioned previously.

(3) Pedisediment--silty or loamy reworked sediments above the stone line (top of the till) in till units (Kenyon, Readlyn, Floyd, Clarion, Nicollet, etc.).

(4) Sediments (above till)--higher sand material between the loess and the underlying till in the shallow loess over till units (Dinsdale, Sac, Clinton variant, etc.) and in the 100-125 cm (40-50 in.) layers of some deep loess units at the shallow end of their range (Tama, Atterberry, and Primghar).

(5) Till--till material below the overlying pedisediment, sediment, or loess material (Shelby, Kenyon, Clarion, etc.).

(6) Paleosol--high clay paleosol in the upper layers of the Kansan glacial till surface (Adair, Clarinda, and Lamoni).

(7) Lacustrine--units having water deposited fine materials primarily in the Clarion-Nicollet-Webster soil association area (Okoboji, Marna, and Guckeen).

(8) Colluvium (below loess soils)--Napier, Judson, and Ely units.

(9) Colluvium (below till soils)--none included in this study.

(10) Alluvium (loess areas)--silty terrace (Nevin and Bremer) and bottomland units (Nodaway, Kennebec, Colo, Zook, Wabash, Vesser, Humeston, Sawmill and Missouri River bottomland units) in the loess soil association areas.

(11) Alluvium (till areas)--terrace (Saude, Waukee, Lawler, Marshan, Wadena, Cylinder, Biscay, and Dempster) and bottomland units (Kennebec, Colo, Coland, Calco, Turlin, and Spillville) in the till soil association areas.

(12) Eolian--eolian loamy fine sand and sandy loam units (Sparta, Chelsea, Dickinson, and Lamont).

For this study, the above parent material groups were combined into 7 classifications from which 6 variables were included in the regression analyses. These transformations will be described later.

Location Variables

The effects of the geographical location of the site within the state on soil test P were determined by using two location variables: (1) for the S-N direction, the legal township number (TWP) was used which varied from TWP65 at the southern edge of Iowa to TWP100 at the northern edge of the state and coded for analyses as TWP minus 65; and (2) for the E-W direction, the legal range number (RANGE) was used which was coded R7E (eastern edge of Iowa) = -06 to R1E = 000 and R1W = 001 to R49W (western edge of Iowa) = 049.

Salih (1979) reported that both TWP and RANGE had significant effects on subsoil STP levels. These probably were indirect effects through their high correlations with the climatic variables of mean annual temperature and rainfall, respectively. In other geographical areas, the S-N and E-W locations may have little usefulness although other directions may be better related to changes in soil parameters.

Profile Variables

Slope and slope configuration

These two variables were included to describe the surface characteristics of the profile site. The slope of the site area (SLOPE), measured with an Abney level or a Clinometer, was listed as the percent slope. The slope configuration of the site area (SLCONF) was coded from 1 = strongly convex to 6 = concave (Appendix Table A1).

Erosion class and thickness of A horizon

The erosion class (EROS) as determined from the profile description was coded as follows: 0 = deposition or no erosion (>30 cm or 12 in. of A horizon), 1 = slight (18-30 cm or 7-12 in. of A horizon), 2 = moderate (7.5-18 cm or 3-7 in. of A horizon with some mixing of B horizon), and 3 = severe (<7.5 cm or 3 in. of A horizon remaining). The thickness of the A horizon (THAHOR) which included the A1 + A2 (if present) + A3 was determined from the profile description and listed as inches of A horizon (later converted to cm).

Natural internal drainage

The natural internal drainage class (DRAIN) of each profile was estimated from the class assigned to the modal Iowa soil types by Fenton et al. (1971) and by the Soil Conservation Service, USDA (1972). The drainage class of many profiles was adjusted after examining the soil profile descriptions of those that deviated from the modal soil type (Henao, 1976). The drainage class was coded for inclusion in the regression analyses from 10 = excessive to 90 = very poor (Appendix Table A1).

Biosequence

The effect of native vegetation on subsoil P was included as the biosequence (BIO) variable, coded as follows:

1 = soil developed under forest

2 = forest-transition intergrade

3 = transition, soil developed under forest and prairie

4 = transition-prairie intergrade

5 = soil developed under prairie.

The classification of each profile was based on the soil profile description.

Soil pH-related variables

The pH-related variables associated with profile development included minimum pH in the subsoil (PHMIN) coded by subtracting 4.5 from all values, depth to the midpoint of the PHMIN horizon or horizons (DPHMIN) later transformed to cm, and depth to the top of the calcareous or carbonate horizon (DCAL) if present in the 152 cm (60 in.) profile.

The depth to the carbonate horizon was determined from the profile description and verified by the horizon pH values. DCAL was originally coded as 60 in. minus depth in inches to the top of the carbonate layer with $\geq$ 60 in. = 0. These values were later transformed to cm and coded values were 152 cm minus depth in cm.

The DCAL variable was listed on original computer card 0 (Appendix Table A1). The PHMIN and DPHMIN variables were listed on Card 1 (Appendix Table A2). These two had been computed and transferred to a new data deck for the first subsoil P study (Salih, 1979), but it was more convenient to list and punch these along with other variables on card 1 for this study.

Maximum clay and depth to maximum clay

Two clay-related variables also associated with soil profile development were maximum percentage clay in the subsoil (CMAX) and depth to the midpoint of the CMAX horizon or horizons (DCMAX) in inches. These were punched on card 1 and DCMAX was later transformed to cm. Salih (1979) reported that DCMAX had significant effects on subsoil P of the index (fixed-depth) layers. He had not included the CMAX variable, but permeability class which was highly correlated with CMAX (r = 0.92) did have a significant effect on subsoil P in the absence of the horizon variables including the clay content of the index layer.

Climatic Variables

Soil scientists agree that climate (precipitation, temperature, and potential evapotranspiration) is one of the most important factors in soil formation. Many have emphasized the direct correlations between soil properties and the climatic variables.

The effects of the site location within a specific geographical area on soil variables should be related to the climatic variables of rainfall, temperature, and potential evapotranspiration. Although the S-N and E-W locations of soil profiles may have a significant relationship with the soil parameters in specific geographical areas such as Iowa, they may have little effect in other geographical areas.

Because Iowa climate from 5,400 to 6,600 years ago to the present, during which much of the soil development has occurred, has been similar (Ruhe, 1969), climatic variables were included in this study and related to changes in subsoil P distributions. These variables have the advantage that they can be used to explain variations in soil parameters in any geographical area in the world where long-term climatic data are available.

<u>Mean annual precipitation and temperature</u>

The data for the mean annual precipitation (PPT) and mean annual temperature (TEMP) were computed by Paul Waite, State Climatologist, and presented by Shaw (1978). The Iowa maps with isolines of the mean annual PPT and TEMP for the 1941-1970 period are shown in Figures 2 and 3, respectively. Values of each site were estimated by transferring the PPT and TEMP isolines of the Iowa maps to the county maps on which the site locations were shown. Isolines for values between the whole numbers in Figures 2 and 3 were drawn on the county maps to facilitate the estimation of the PPT and TEMP values for each site as shown for Woodbury

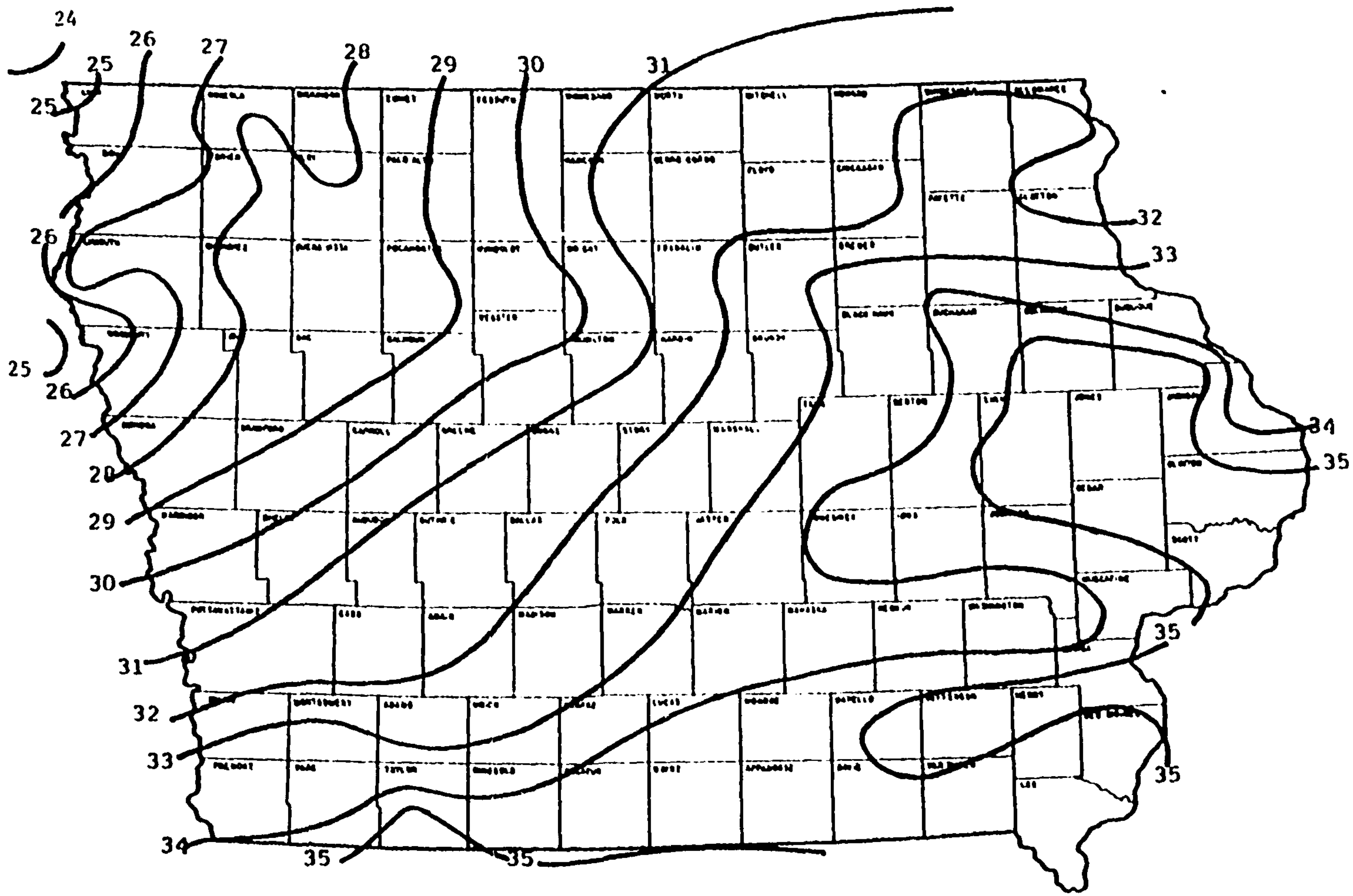

Figure 2. Iowa mean annual precipitation isolines in inches for the 1941-70 period (data from Paul Waite, State Climatologist, Des Moines, Iowa)

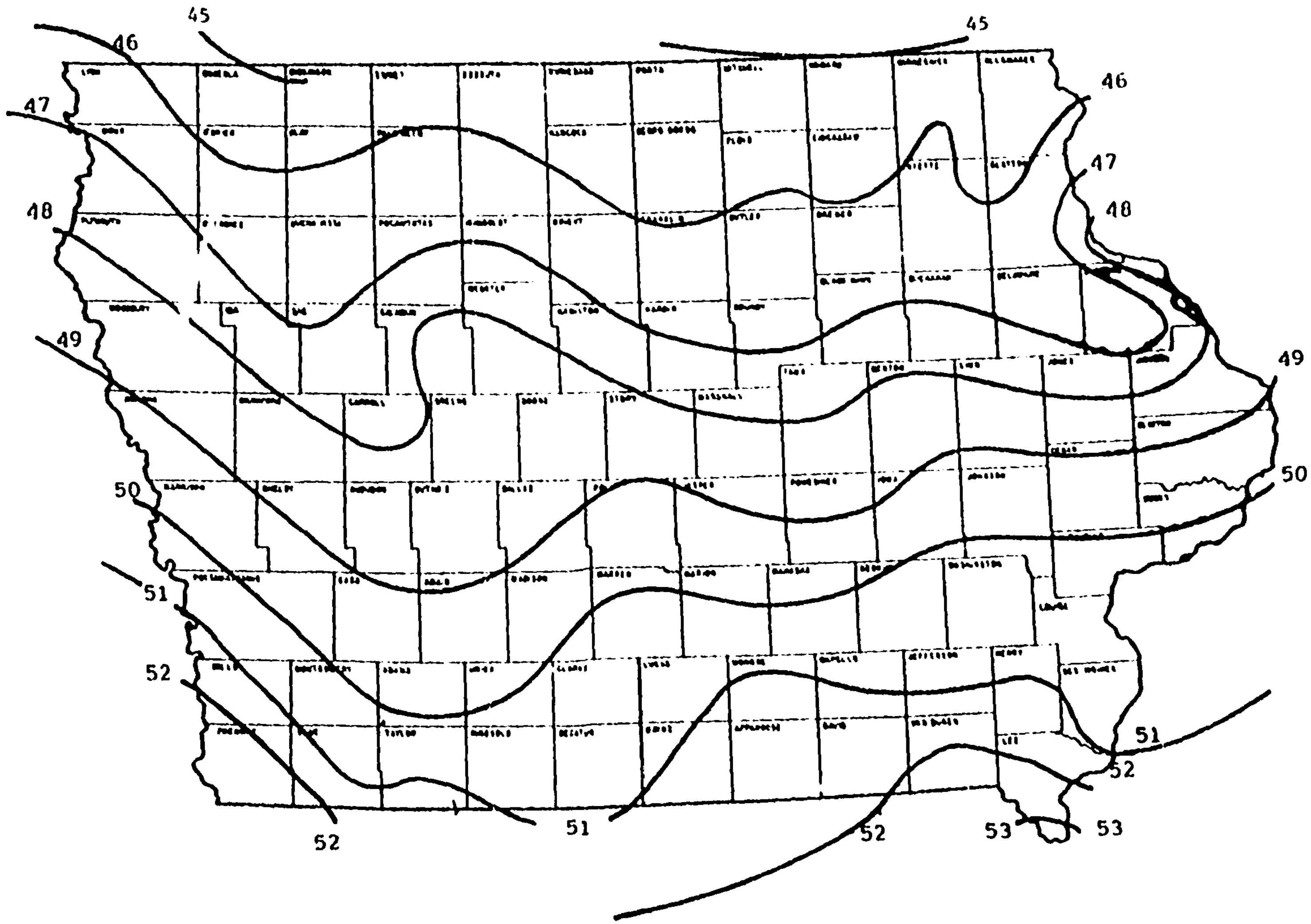

Figure 3. Iowa mean annual temperature isolines in °F for the 1941-70 period (data from Paul Waite, State Climatologist, Des Moines, Iowa)

County in Figure 4.

The estimated values of PPT were punched on card 1 (Appendix Table A2) as inches of precipitation. These values were transformed to cm, coded by subtracting 63.0, and then transferred to the new data card (Appendix Table A3).

The estimated TEMP values for each site were punched on card 1 (Appendix Table A2) in both °F and °C. The °C values for TEMP were coded by subtracting 7.0 and then transferred to the new data card (Appendix Table A3).

Mean annual potential evapotranspiration

The data for potential evapotranspiration (PE) were obtained from Mather (1965). He listed the mean annual and monthly values (computed from 1931-1960 weather data) for selected Weather Bureau stations in Iowa and surrounding states. These data for PE in mm of water are shown on the Iowa map (Figure 5). Ranges of PE values across the counties were then estimated in the general direction of the changes across that area of state (Table 1). The PE values for the Sioux City and Omaha Weather Bureau stations were not used because they were much higher than those of nearby stations. The PE isolines for each county were then drawn on the county map to facilitate the estimation of PE values for each site.

The PE values in cm for each site in each county were punched on card 1 (Appendix Table A2). These were coded by subtracting 62.0 and then transferred to the new data card (Appendix Table A3).

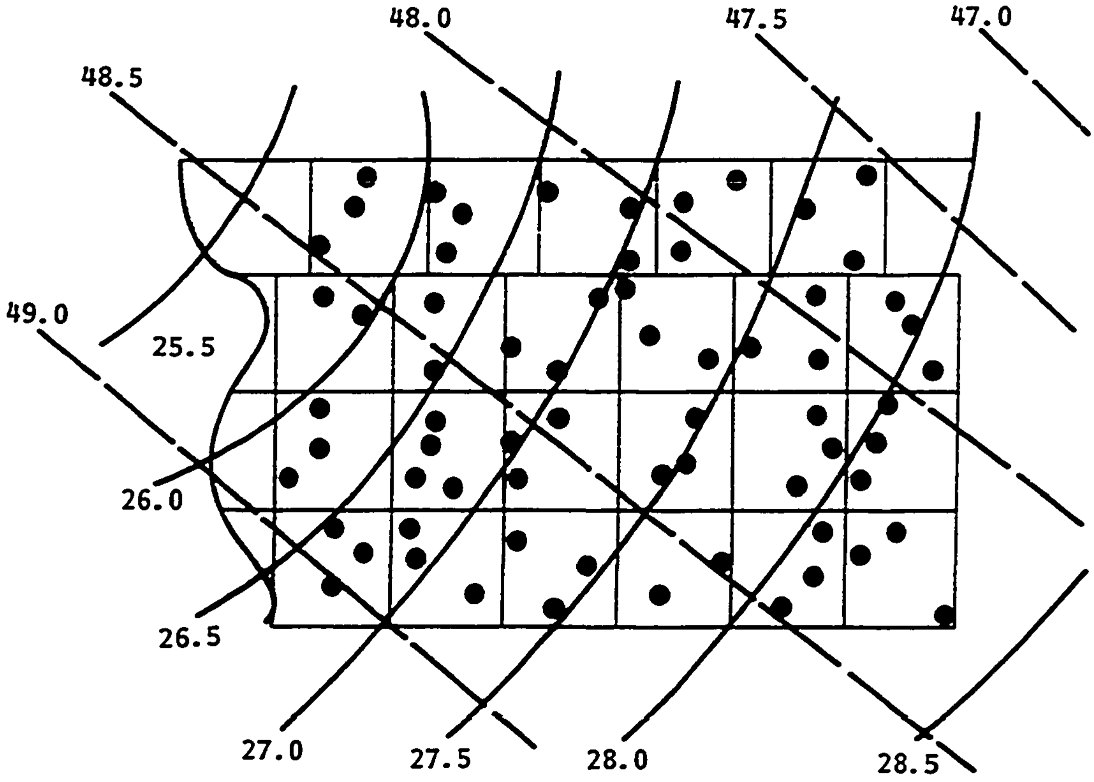

Figure 4. Mean annual precipitation isolines in inches (solid lines) and temperature isolines in °F (dashed lines) for Woodbury County (dots show site locations)

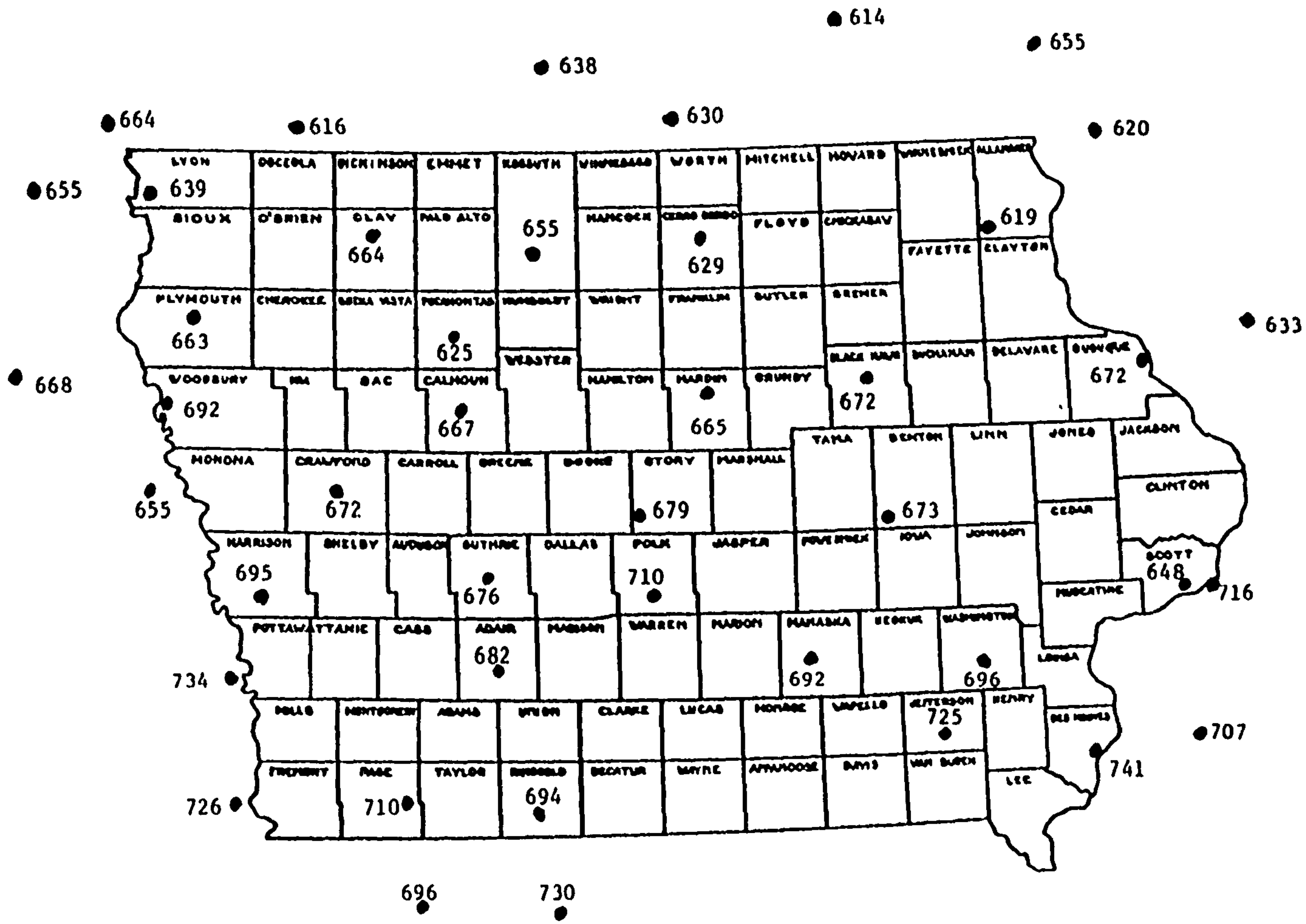

Figure 5. Mean annual potential evapotranspiration (PE) in mm for the 1931-60 period for Weather Bureau stations in Iowa and surrounding states (data from Mather, 1965)

Table 1. Estimated potential evaporation (PE) values across each of the 15 counties

County	Direction of change	Range of PE values (mm)
Adams	NE to SW	686-696
Bremer	N to S	648-658
Cass	NE to SW	682-694
Clay	N to S	648-658
Crawford	NE to SW	664-682
Fayette	NE to SW	638-658
Hamilton	NE to SW	662-672
Harrison	NE to SW	682-700
Howard	N to S	626-634
Keokuk	N to S	690-698
Linn	N to S	670-682
Lyon	NE to SW	642-654
Muscatine	N to S	690-698
Wayne	N to S	702-710
Woodbury	NE to SW	664-686

Statistical Analysis

Transformed data from original data cards

The original data associated with each described soil horizon of the profile were punched on cards 0 and 1; descriptions of these data are given in Appendix Tables A1 and A2. The data needed from the two original data cards were then combined on a new data card; a program was written to transfer or to transform the data for the variables to the new card, one card for each horizon of each profile. In the program of computing and transferring the data to the new card, all measurements of the variables were transformed to metric units and many were coded as described in previous sections. The instructions for writing the computer program for transferring, transforming, and combining the data from the original cards to the new data deck are given in Appendix Table A3.

The soil parent material of each horizon was initially classified into 1 of 12 parent material groups on the original data card, as described previously. For this study, the soil parent material groups were combined into seven classifications to decrease the number of variables in the analyses.

The initial parent material groups and the final groups are given in Table 2. The deep loess soils with either oxidized or deoxidized

Table 2. Number of observations (soil horizons) in each parent material group before and after combining for regression analysis

Initial parent material group	No. of horizons	Final parent material group	No. of horizons
Loess (oxidized)	1681	LOESS	1893
Loess (deoxidized in 127 cm or 50 in. profile)	212		
Pedisediment (upper horizons)	425	PEDISED	588
Sediments above till	105		
Lacustrine above till	58		
Till in 127 cm profile	627	TILL	746
Paleosol in 127 cm profile	119		
Colluvium below loess soils	119	COLLUV-L	119
Alluvium in loess areas	293	ALLUV-L	293
Alluvium in till areas	179	ALLUV-T	179
Eolian LFS and FSL	95	EOLIAN	95
Total number of horizons			3913

loess material were combined into the LOESS group which was the largest group of soil parent materials. Several initial parent material classifications (pedisediment, sediments above till, and lacustrine materials) that occurred in the till parent material areas were combined into the pedisediment (PEDISED) group. The till and paleosol parent materials were combined into the TILL group, the second largest group of parent materials. The colluvium below loess (COLLUV-L), alluvium in the loess and till areas (ALLUV-L and ALLUV-T), and eolian sand (EOLIAN) groups were used as originally listed.

The instructions for transferring or combining and transferring the parent material groups are given in Appendix Table A3.

Multiple regression model

Multiple regression analysis was used to provide estimates of the effects of many variables[1] on the available soil test P (STP) distributions in the subsoil. All computations were carried out with respect to the model:

$$Y_i = B_0 + B_1X_{1i} + B_2X_{2i} + \ldots + B_pX_{pi} + \varepsilon_i \quad , \qquad (1)$$

which is the usual multiple regression model having Y_i as the dependent variate, the explanatory factors X_{1i}, X_{2i}, ... X_{pi} which are assumed to be independent, ε_i which is the error term because the postulated independent variates do not completely explain Y_i, and the parameters B_0,

[1]The term "variable" will refer to a factor under study whose effect in the regression model and analysis may be a function of one or more variates or terms (X_i). "Variate" will refer to a single term included in the multiple regression model and analysis.

B_1, ... B_p which are the population regression coefficients. The usual assumptions in the regression analyses were made except that it was recognized that the X's in these data were intercorrelated to a varying degree. Pena-Olvera (1979) studied the intercorrelations among the soil variables used in this study and presented an extensive discussion of the effects of intercorrelation on the results of multiple regression analysis.

The criteria for retention of given variates in the model were: (1) after the t-test for significance was applied to each of the partial regression coefficients, only those were retained in the equation whose probability was less than $\alpha = 0.10$ initially and less than $\alpha = 0.05$ in final stages of model selection except that the linear variate was retained regardless of its significance if its squared or any interaction variate was significant at $\alpha = 0.05$; (2) a lower-order interaction variate of DEPTH was retained regardless of its significance if a higher-order interaction was significant at $\alpha = 0.05$; (3) except for the initial models, no variables were to be included with correlations > ±0.60; and (4) after comparing correlated variables in alternate models, the one of the pair that gave the higher R^2 was retained in subsequent models and the other was deleted.

In the first stage of the statistical analysis, the correlations between subsoil P levels (STP) and the independent variables and between all independent variables were examined. In the second stage, a series of models including the cubic function of DEPTH and linear and quadratic functions of the other variables were computed to estimate the linear and curvilinear effects of the variables on STP levels and to select which of the highly correlated variables were to be retained in subsequent models. In the third stage, the significant linear*linear, quadratic*linear, and cubic*linear interactions between DEPTH and all other variables were selected. In the final stage, selected linear, squared, and cubic terms for the variables and selected interactions with DEPTH were included in a full model with selected interactions between all other variables. Model selection was by stepwise, backward elimination of non-significant variates using the criteria in the previous paragraph.

The fitting of the multiple regression equations was done by using the Helarctos II computer program (Kennedy, 1971). This program is particularly well-adapted to fit models by the least squares method because of its built-in facility to create different functions out of the columns of the X matrix containing a maximum of 100 independent variates. All the regression statistics from the regression analysis were printed in the computer output as options.

Interpretation of quadratic functions

The quadratic effect of any variable (X_i) on STP (soil test P in the subsoil) in the quadratic model can be computed by taking the partial derivative of STP with respect to the X_i variable, which is,

$$dSTP/dX_i = b_i + 2b_{ii}X_i \quad , \tag{2}$$

where b_i and b_{ii} = the regression coefficients of the linear and squared variates, respectively. The partial derivative in equation 2 gives the slope of the curve, or the change in STP per unit change in X_i, at any level of X_i with all other variables held constant. Because equation 2 is a linear function of X_i, the slope changes linearly with change in X_i.

The value of X_i that gives the maximum or minimum STP is obtained by setting the partial derivative in equation 2 equal to 0 and solving for X_i,

$$b_i + 2b_{ii}X_i = 0 \qquad \text{and}$$

$$X_i = -b_i/2b_{ii} \quad . \tag{3}$$

If the sign of b_i is positive and that of b_{ii} is negative in equation 2, the quadratic function has a maximum value of STP for some positive level of X_i; if the signs of the coefficients are reversed, the function has a minimum STP for some positive level of X_i. If signs of both coefficients are negative, the computed maximum STP is at a negative X_i, and outside of the relevant range; in the relevant range, STP decreases at an increasing rate (higher negative slope) as X_i increases. If signs of both are positive, the computed minimum at a negative X_i and outside of the relevant range; in the relevant range, STP increases at an increasing rate (higher positive slope) as X_i increases.

Interpretation of linear and quadratic functions with interactions

The effects of a variable which has a linear or curvilinear effect on STP modified by linear*linear interactions can be determined by taking the partial derivative of the STP regression equation with respect to the variable. For a variable, X_1, having a linear function plus interactions with two other variables, X_2 and X_3, in the STP regression equation, the terms in the regression equation giving the effect of X_1 on STP are b_1X_1, $b_2X_1X_2$, and $b_3X_1X_3$, where b_1 to b_3 are the partial regression coefficients for X_1 and the interactions of X_1X_2 and X_1X_3, respectively.

The partial derivative of STP with respect to X_1 is,

$$dSTP/dX_1 = b_1 + b_2X_2 + b_3X_3 \quad . \qquad (4)$$

Equation 4 gives the slope (change in STP per unit change of X_1) of the linear response of STP to X_1 at any level of X_2 and X_3. Thus, the presence of interactions alters the slope of the linear response of STP to X_1. To get the slope of STP on X_1 at fixed levels of X_2 and X_3, the means or any other selected values of X_2 and X_3 are substituted into equation 4; the products of b_2X_2 and b_3X_3 are then added to b_1 to give the slope of the linear function of STP on X_1.

If the X_1 variable has a quadratic (curvilinear) function plus interactions with two other variables (X_2 and X_3) in the STP regression equation, the relevant terms in the equation are b_1X_1, $b_{11}X_1^2$, $b_2X_1X_2$, and $b_3X_1X_3$, where b_1, b_{11}, b_2, and b_3 are the partial regression coefficients for X_1, X_1^2, X_1X_2, and X_1X_3, respectively. The partial derivative then is,

$$dSTP/dX_1 = b_1 + 2b_{11}X_1 + b_2X_2 + b_3X_3 \quad . \qquad (5)$$

Equation 5 gives the slope (change in STP per unit change in X_1) of the STP response curve at any level of X_1, X_2, and X_3.

To get the simplified partial derivative of STP on X_1 at fixed levels of X_2 and X_3, the means or any other selected values of X_2 and X_3 are substituted into equation 5; the products of b_2X_2 and b_3X_3 are then added to b_1 to give the simplified derivative of STP on X_1 at fixed levels of X_2 and X_3. This equation (which is the same as equation 2) can be used to compute the X_1 that gives the minimum or maximum STP as shown in equation 3.

Another way to determine the level of X_1 that gives the minimum or maximum STP from the partial derivative of STP with respect to X_1 is to set equation 5 equal to 0 and solve for X_1, as follows:

$$0 = b_1 + 2b_{11}X_1 + b_2X_2 + b_3X_3 \quad ,$$

$$2b_{11}X_1 = -b_1 - b_2X_2 - b_3X_3 \quad , \quad \text{and}$$

$$X_1 = \frac{-b_1 - b_2X_2 - b_3X_3}{2b_{11}} \quad . \tag{6}$$

The interactions not only alter the slope of the response of STP on X_1 in equation 5 but also change the value of X_1 that gives the minimum or maximum STP in equation 6. That is, minimum or maximum STP will be associated with lower or higher levels of X_1 as levels of the interaction variables change. To determine X_1 at minimum or maximum STP, fixed values of X_2 and X_3 are substituted into equation 6, the products of b_2X_2 and b_3X_3 are added to b_1, and X_1 then is computed. As the number of interactions increases, the interpretation of the effects of variables on STP becomes more complex.

<u>Interpretation of the cubic function of depth</u>

The cubic function of the depth variable (DEPTH) was included in the regression analyses. The terms in the STP regression models without interactions for the cubic effect of DEPTH (X_1) on STP are b_1X_1, $b_2X_1^2$ and $b_3X_1^3$, where b_1 to b_3 are the partial regression coefficients of the linear, quadratic, and cubic terms or variates, respectively.

The partial derivative of STP with respect to X_1 (DEPTH) is:

$$dSTP/dX_1 = b_1 + 2b_2X_1 + 3b_3X_1^2 \quad . \tag{7}$$

This partial derivative gives the slope of the cubic function, or change in STP per unit change in X_1, at any X_1 level (DEPTH) with all other variables held constant. Because equation 7 is a quadratic function of X_1, the slope changes in a quadratic manner with changes in X_1.

The values of X_1 that give the minimum STP (STPMIN) and maximum STP (STPMAX) in the cubic function are obtained by setting the partial derivative in equation 7 equal to 0 and then solving for X_1, using the quadratic formula in which $3b_3 = a$, $2b_2 = b$, and $b_1 = c$, as follows:

$$b_1 + 2b_2X_1 + 3b_3X_1^2 = 0 \quad , \quad \text{and}$$

$$X_1 = \frac{-2b_2 \pm [(2b_2)^2 - 4(3b_3b_1)]^{\frac{1}{2}}}{2(3b_3)} \quad . \tag{8}$$

At slope = 0, X_1 has two values, one associated with STPMIN and the other with STPMAX. To determine which value is associated with STPMIN and which one with STPMAX, the second partial derivative of the cubic function of STP with respect to X_1 is obtained, as follows:

$$d^2STP/d^2X_1 = 2b_2 + 6b_3X_1 \quad . \tag{9}$$

Both values of X_1 computed from equation 8 are substituted into equation 9; the one that gives a positive value is associated with STPMIN and the one that gives a negative value is associated with STPMAX. In almost all cases in this study, the lesser X_1 value from equation 8 gave STPMIN and the greater X_1 value gave STPMAX in the cubic effect of DEPTH on STP.

<u>Interpretation of linear and quadratic functions of variables having interactions with depth</u>

The complex interactions of DEPTH (X_1) with all other variables (X_i) on STP were investigated in this study. These were the linear*linear (X_1*X_i), quadratic*linear (X_1^2*X_i), and cubic*linear (X_1^3*X_i) interactions. The effects of the variables (other than DEPTH) on STP may be linear or quadratic modified by 1, 2, or 3 of the interactions with DEPTH.

The simplest case is a linear effect of a variable (X_2) on STP modified by a linear*linear interaction with DEPTH (X_1). The relevant terms in the STP regression equation are b_1X_2 and b_2X_1*X_2. The partial derivative is:

$$dSTP/dX_2 = b_1 + b_2X_1 \quad . \tag{10}$$

The linear slope of the STP response on X_2 thus varies linearly with X_1 (depth in the soil profile).

If the X_2 variable has a linear effect on STP modified by linear* linear (X_1*X_2) and quadratic*linear (X_1^2*X_2) interactions, the relevant terms in the STP regression are b_1X_2, $b_2X_1*X_2$, and $b_3X_1^2*X_2$. The partial derivative is:

$$dSTP/dX_2 = b_1 + b_2X_1 + b_3X_1^2 \quad . \tag{11}$$

The linear slope of the STP response on X_2 thus varies curvilinearly (in a quadratic manner) with X_1 (DEPTH). To determine the depth in the profile where the slope of the STP response on X_2 is a minimum or a maximum, the partial derivative of equation 11 with respect to X_1 (DEPTH) is obtained as follows:

$$d(dSTP/dX_2)/dX_1 = b_2 + 2b_3X_1 \quad . \tag{12}$$

Equation 12 is set = 0 and solved for X_1. The slopes computed from equation 11 can be plotted for various depths in the profile to illustrate the curvilinear change in STP responses on X_2 levels with depth.

If the X_2 variable has a linear effect on STP modified by all three interactions with X_1 (DEPTH), the equations in the previous paragraph are expanded to include the $X_1^3*X_2$ interaction term. The linear slope of the STP response on X_2 thus varies in a cubic manner with depth in the profile. The depths where the minimum and maximum slopes ($dSTP/dX_2$) occur can be computed from the derivative of $dSTP/dX_2$ with respect to depth (X_1) as in equation 12 by using the quadratic formula as was done in equation 8.

If the X_2 variable has a quadratic (curvilinear) effect on STP modified by only a linear*linear (X_1*X_2) interaction with DEPTH (X_1), the relevant terms in the STP regression equation are b_1X_2, $b_2X_2^2$, and

$b_3X_1*X_2$. The partial derivative is:

$$dSTP/dX_2 = b_1 + 2b_2X_2 + b_3X_1 \quad . \qquad (13)$$

The slope of the STP response on X_2 varies with levels of both X_2 and X_1 (DEPTH). The initial slopes of the quadratic function at $X_2 = 0$ and the levels of X_2 associated STPMIN or STPMAX vary linearly with increasing X_1 (depth in the profile). If the changes in STP (ΔSTP) are plotted against increasing levels of X_2 at various depths in the profile, the magnitudes of the STP response curves also change linearly with depth.

If the X_2 variable has a quadratic effect on STP modified by two of the interactions with DEPTH, X_1*X_2 and $X_1^2*X_2$, the relevant terms in the regression are b_1X_2, $b_2X_2^2$, $b_3X_1*X_2$, and $b_4X_1^2*X_2$. The partial derivative is:

$$dSTP/dX_2 = b_1 + 2b_2X_2 + b_3X_1 + b_4X_1^2 \quad . \qquad (14)$$

The initial slopes of the quadratic function at $X_2 = 0$ and the levels of X_2 associated with STPMIN or STPMAX vary in a quadratic manner with increasing X_1 (depth in the profile). The magnitudes of the STP response curves (ΔSTP on X_2) also change curvilinearly with X_1; they may increase to a maximum at a certain depth and then decrease. The depth in the profile associated with the minimum or maximum change in STP on X_2 levels can be determined by taking the partial derivative of equation 14 with respect to X_1 as shown in equation 12, setting = 0, and solving for X_1.

For the quadratic effect of the X_2 variable on STP modified by all three interactions with DEPTH (X_1), the relevant terms in the STP regression equation are b_1X_2, $b_2X_2^2$, $b_3X_1*X_2$, $b_4X_1^2*X_2$, and $b_5X_1^3*X_2$. The partial derivative is:

$$dSTP/dX_2 = b_1 + 2b_2X_2 + b_3X_1 + b_4X_1^2 + b_5X_1^3 \ . \quad (15)$$

The initial slopes of the quadratic function at $X_2 = 0$, levels of X_2 associated with STPMIN or STPMAX, and magnitudes of the ΔSTP response curves on X_2 all change in a cubic manner with increasing X_1 (DEPTH). They may decrease initially with increasing X_1 to a minimum, then increase to a maximum, and then decrease again in the lower soil profile. The depths associated with the minimum and maximum changes can be computed from the partial derivative of equation 15 with respect to X_1 as in equation 12 and then by using the quadratic formula as in equation 8.

If the interactions between the particular X_i studied and other X_i variables occur in the STP regression equation, these are included in the partial derivative of STP with respect to the particular X_i. These add to the complexity of determining the effects of this X_i variable on STP. The levels of the other X_i can be held constant, the partial derivative then can be simplified, and the relationships between STP and the X_i of interest then can be determined at various depths in the profile as described previously.

Interpretation of the cubic function of depth with interactions

The effect of the cubic function of DEPTH on STP was influenced by many interactions with other variables, including the linear*linear, quadratic*linear, and a few cubic*linear interactions between DEPTH and the other variables. The partial derivative of STP with respect to DEPTH becomes cumbersome to handle because more than 20 terms may be included. To study the effect of the interaction or interactions between DEPTH and one variable on STP, all other variables can be fixed at their means or selected values and the partial derivative simplified by collecting terms. The constant and the coefficients of the DEPTH and $DEPTH^2$ terms in the simplified partial derivative thus are affected by the selected levels of the other variables. The effects on STP of the DEPTH interactions with only one variable will be discussed in this section.

If the effect of DEPTH (X_1) on STP is modified by a linear*linear interaction with another variable (X_2), the relevant terms in the STP regression equation are b_1X_1, $b_2X_1^2$, $b_3X_1^3$, and $b_4X_1*X_2$. The partial derivative is:

$$dSTP/dX_1 = b_1 + 2b_2X_1 + 3b_3X_1^2 + b_4X_2 \quad . \qquad (16)$$

As the level of X_2 is varied, the initial slope at $X_1 = 0$, the slope of the STP response on X_1 (DEPTH) at a fixed depth, and the X_1 values associated with STPMIN and STPMAX are changed. The curvature of the cubic effect of X_1 on STP is not changed because the coefficients for X_1 and X_1^2 in equation 16 are not affected by X_2. The X_1 levels associated with STPMIN and STPMAX at selected levels of X_2 can be obtained by setting equation 16 = 0 and solving as shown in equation 8.

If the effect of DEPTH on STP is modified by two interactions, the linear*linear and quadratic*linear terms, the relevant terms in the STP regression equation are b_1X_1, $b_2X_1^2$, $b_3X_1^3$, $b_4X_1*X_2$, and $b_5X_1^2*X_2$. The partial derivative is:

$$dSTP/dX_1 = b_1 + 2b_2X_1 + 3b_3X_1^2 + b_4X_2 + 2b_5X_1*X_2 \quad . \tag{17}$$

As the level of the interacting variable, X_2, increases, both the constant and the coefficient of X_1 are changed. The curvature of the STP response to DEPTH thus varies with the level of the X_2 variable.

If the effect of DEPTH on STP is modified by all three interactions (linear*linear, quadratic*linear, and cubic*linear) with X_2, the relevant terms in the regression equation are b_1X_1, $b_2X_1^2$, $b_3X_1^3$, $b_4X_1*X_2$, $b_5X_1^2*X_2$, and $b_6X_1^3*X_2$. The partial derivative is:

$$dSTP/dX_1 = b_1 + 2b_2X_1 + 3b_3X_1^2 + b_4X_2 + 2b_5X_1*X_2 + 3b_6X_1^2*X_2 \ . \tag{18}$$

As X_2 increases, the constant and the coefficients of the X_1 and X_1^2 terms in equation 18 are changed. Thus, the curvature of the STP response on DEPTH can be changed drastically if all three interactions involving DEPTH are present.

Interpretation of the variable effects in the final prediction model

The final prediction model for STP contained so many interactions between the DEPTH variable and other variables and between the other variables that the interpretations of the effects of the variables on STP were difficult. To illustrate the interactive effects of DEPTH and two other variables on STP distributions in the profile, a computer program was written to predict STP levels for all combinations of selected levels of DEPTH and several levels of two other variables.

The intercept and the regression coefficients of all variates in the final STP prediction equation were entered into the computer, all other variables were set at constant levels, and levels of DEPTH and two other X_i variables were specified. The predicted STP values for all combinations of the three variables were then computed and printed in the output. For selected levels of the two variables, the STP distributions with DEPTH were then plotted to illustrate their interaction effects on STP.

RESULTS AND DISCUSSION

In the initial study of subsoil P levels in Iowa soils, Salih (1979) regressed the soil test P levels of two fixed layers, 30-51 cm deep (STP1) and 76-107 cm deep (STP2), on soil and location variables. He developed multiple regression equations including the most important soil and location variables to predict the STP1 and STP2 levels in these two fixed layers in the subsoil. Also, in the same study, he investigated the relative importance of the parent material, horizon, and profile variables for predicting STP1 and STP2.

This research is the continuation of the previous research. The major objective was to develop prediction equations for subsoil P distributions (STP) with profile depth in order to predict the STP level at any depth in the profile, using the soil and location variables found to be most important in the previous study plus the depth and climatic variables included in this study.

The results of this research on the effect of selected soil, location, depth, and climatic variables on subsoil P levels in Iowa soils will be discussed in six sections. In the first section, simple averages of minimum and maximum subsoil P, soil pH, and clay parameters in the soils of selected parent material, soil series, and mapping unit groups are presented to illustrate the variation among soils. In the second section, the simple correlation analysis to detect the intercorrelations among the variables used in this study is presented and discussed.

The third section involves the multiple regression analyses of STP on linear functions of the parent material variables, the cubic function of depth in the profile (DEPTH), and quadratic functions of all other variables. In these series of regression models, the relative importance of the location and climate variables are tested in an alternate series of models for predicting STP. The relative effects of the horizon and genetic horizon variables on STP are also tested. The most important variables are selected for further testing.

The fourth section involves testing the interactions between the linear, quadratic, and cubic functions of DEPTH and all variables selected previously in one series and with all except the horizon variables in another series of STP regression models. The significant $DEPTH*X_i$, $DEPTH^2*X_i$, and $DEPTH^3*X_i$ interactions will be presented and discussed.

The fifth section involves testing the effects on STP of many interactions between the other variables in the presence of linear, quadratic, and cubic functions of selected variables and the DEPTH interactions selected in the previous series of regressions. The final prediction equation of STP on selected variates, including the horizon variates, will be presented and discussed.

The sixth and final section involves selection of the STP interaction model on all selected variables except the horizon variables. Interactions among the variables are tested and selected in the presence of the linear, quadratic, and cubic functions of the variables and the DEPTH interactions selected previously. Final prediction models, without and with the genetic horizon variable, will be presented and discussed.

Average Minimum and Maximum Subsoil P Levels of Selected Soil Series and Mapping Unit Groups

To show the differences in subsoil P levels among soils, simple averages were computed of the minimum (STPMIN) and maximum (STPMAX) soil test P levels of selected parent material, soil series, and mapping unit groups. The STPMIN and STPMAX values were used because these values could be determined readily from the raw profile data. Average depth to STPMAX (DPMAX) was also computed for the soil groups with sigmoid (S-shaped) P distributions. To characterize the soil profile development, the average values for minimum pH in the profile (PHMIN), depth to minimum pH (DPHMIN), maximum percentage clay in the profile (CMAX), and depth to maximum clay (DCMAX) were also computed for each group. The average values for all of these variables are shown in Table 3. The grouping of mapping units is more detailed than was done previously (Salih, 1979). Information about average subsoil K levels in various Iowa soil groups was given by Ghaffarzadeh (1979).

Before averaging the soil test P values of the selected groups, the profiles were divided into two subsoil P distribution curves or patterns, sigmoid and decreasing with depth, if both occurred. In the sigmoid distribution, the subsoil P level was minimum immediately below the plow layer or decreased to a minimum in the upper profile; it then increased to a maximum in the deeper part of the profile. In some till soils and soils with calcareous horizons deeper in the profile, the subsoil P level below the STPMAX layer often was less than the STPMIN level in the upper profile. For the average STPMIN levels in Table 3, the STPMIN level in the upper profile was used. For those with the sigmoid

Table 3. Average soil test P, soil pH, and clay parameters in the subsoils of selected parent material, soil series, and mapping unit groups

Soil group or mapping unit	No. sites	Distr. curve[b]	Soil parameter[a]						
			PMIN (pp2m)	PMAX (pp2m)	DPMAX (cm)	PHMIN (pH)	DPHMIN (cm)	CMAX (%)	DCMAX (cm)
Deep loess-derived soils									
Moody: EROS=0,1[c]	4	SIG	9	15	102	6.3	24	33	37
	3	DECR	5	13	--	6.1	22	34	34
EROS=2	2	SIG	11	15	108	6.6	23	32	28
	1	DECR	6	9	--	7.1	29	33	29
Moody (<91 cm to CO_3):									
EROS=0,1	3	DECR	5	11	--	6.6	24	34	33
EROS=2	5	DECR	4	9	--	6.7	20	34	26
Galva (Lyon Co.): EROS=0,1	3	SIG	10	18	101	6.4	23	33	23
	3	DECR	5	13	--	6.1	27	34	23
Galva (Lyon Co., <91 cm to CO_3): EROS=0,1	4	DECR	4	9	--	6.5	22	33	22
Galva (Wood. Co.): EROS=0,1	2	SIG	12	25	97	5.8	38	33	33
EROS=2	1	SIG	11	18	112	6.2	23	33	23
Trend (Lyon Co.)	2	SIG	9	20	97	6.4	29	33	38
	3	DECR	4	9	--	7.1	24	35	24
Primghar, Marcus (Clay, Lyon)	15	DECR	5	11	--	6.5	26	38	29
Monona: EROS=0,1	12	SIG	8	16	104	6.5	29	26	44
	2	DECR	5	12	--	6.9	25	28	45
EROS=2,3	10	SIG	11	17	94	6.6	23	28	23

[a]PMIN = minimum P, PMAX = maximum P, DPMAX = depth to PMAX, PHMIN = minimum pH, DPHMIN = depth to minimum pH layer, CMAX = maximum clay, and DCMAX = depth to maximum clay layer.

[b]SIG = sigmoid; DECR = decreasing.

[c]EROS = erosion class; if not listed, EROS = 0 or 1.

Table 3. (Continued)

Soil group or mapping unit	No. sites	Distr. curve[b]	Soil parameter[a] PMIN (pp2m)	PMAX (pp2m)	DPMAX (cm)	PHMIN (pH)	DPHMIN (cm)	CMAX (%)	DCMAX (cm)
Monona (<91 cm to CO_3):									
EROS=0,1	4	DECR	6	12	--	6.7	23	27	27
EROS=2,3	6	SIG	10	13	54	7.2	23	25	23
	5	DECR	4	10	--	7.4	23	25	23
Knox: EROS=2,3	7	SIG	24	41	80	6.6	34	29	26
Ida, Dow: EROS=2,3	34	DECR	5	7	--	8.1	25	19	27
Marshall: EROS=0,1	36	SIG	13	31	103	6.1	28	34	45
EROS=2	11	SIG	14	24	96	6.4	24	33	33
Sharpsburg: EROS=0,1	12	SIG	11	29	110	6.0	27	37	52
EROS=2	5	SIG	10	23	108	6.2	24	36	34
Macksburg	6	SIG	11	47	120	5.9	33	38	74
Winterset	2	SIG	10	34	92	6.0	36	42	69
Seymour: EROS=1	9	SIG	8	21	107	5.6	26	51	57
EROS=2	3	SIG	8	17	93	5.7	25	47	40
Kniffin: EROS=2	1	SIG	17	50	84	5.4	34	45	41
Edina	6	SIG	9	21	112	5.7	34	54	66
Otley, Nira: EROS=0,1	9	SIG	10	28	106	5.7	34	37	55
Mahaska	9	SIG	11	39	99	5.6	38	39	65
Taintor	4	SIG	8	14	112	6.1	27	40	57
	2	DECR	4	10	--	6.4	23	42	44
Ladoga, Hedrick: EROS=2	3	SIG	20	40	80	5.6	34	38	42
EROS=3	3	SIG	19	37	79	5.9	32	38	32
Givin	4	SIG	10	52	103	5.7	56	39	65
Clinton: EROS=1	1	SIG	18	82	108	5.6	42	38	55
EROS=2,3	2	SIG	30	66	81	5.6	47	38	30
Keomah	1	SIG	11	56	116	5.3	62	40	79

Table 3. (Continued)

Soil group or mapping unit	No. sites	Distr. curve[b]	Soil parameter[a]						
			PMIN (pp2m)	PMAX (pp2m)	DPMAX (cm)	PHMIN (pH)	DPHMIN (cm)	CMAX (%)	DCMAX (cm)
Tama: EROS=0,1	8	SIG	11	47	103	5.6	52	32	63
EROS=2	2	SIG	12	37	90	5.9	29	31	53
Muscatine	2	SIG	11	17	82	5.7	46	36	58
Garwin	1	SIG	9	16	109	5.7	26	37	57
Downs: EROS=0,1	7	SIG	18	68	96	5.6	57	32	59
EROS=2	2	SIG	14	61	100	5.5	56	29	55
Atterberry	4	SIG	11	33	107	5.4	41	36	66
Fayette: EROS=0,1	4	SIG	24	81	82	5.3	54	31	63
EROS=2	9	SIG	36	76	70	5.8	54	27	46
EROS=3	3	SIG	32	78	66	5.7	47	29	28
Stronghurst	1	SIG	10	59	112	5.3	50	38	80
Orwood: EROS=2,3	2	SIG	26	67	92	5.8	64	21	55
Till-derived soils									
SW Iowa (Kansan):									
Shelby: EROS=1-3	2	SIG	8	17	94	6.4	38	36	56
	7	DECR	5	10	--	6.5	26	34	47
Adair: EROS=1-3	4	SIG	7	17	110	5.9	30	50	65
	3	DECR	4	9	--	6.3	21	46	75
Clarinda: EROS=1,2	4	DECR	5	11	--	6.3	27	51	81
Wayne, Keokuk (Kansan):									
Shelby: EROS=0	2	SIG	8	14	100	5.5	37	37	76
EROS=0,2	2	DECR	4	8	--	5.6	22	37	40
Gara: EROS=2,3	2	SIG	8	22	93	5.2	34	36	43
Adair: EROS=1,2	4	DECR	4	9	--	5.5	35	47	50
Clarinda, Lamoni: EROS=1-3	11	DECR	4	9	--	5.6	27	53	73

Table 3. (Continued)

Soil group or mapping unit	No. sites	Distr. curve[b]	Soil parameter[a] PMIN (pp2m)	PMAX (pp2m)	DPMAX (cm)	PHMIN (pH)	DPHMIN (cm)	CMAX (%)	DCMAX (cm)
Clay, Hamilton (Cary):									
Everly	2	SIG	9	18	97	5.9	29	33	70
	4	DECR	4	11	--	6.2	27	32	58
Clarion	13	DECR	5	13	--	6.0	24	25	43
Nicollet	11	DECR	5	11	--	6.6	28	29	55
Webster	12	DECR	5	11	--	7.1	26	35	40
Canisteo, Harps	5	DECR	4	8	--	8.1	22	30	41
NE Iowa (Iowan):									
Ostrander, Aredale	4	SIG	8	18	106	5.5	34	27	63
Kenyon: EROS=0,1	5	SIG	9	14	113	5.5	42	27	61
EROS=0,1	15	DECR	6	14	--	5.6	36	27	71
EROS=2	2	DECR	4	8	--	5.5	33	32	55
Readlyn	13	DECR	5	11	--	5.5	34	29	65
Tripoli	5	DECR	4	10	--	6.7	28	31	50
Floyd	23	DECR	5	11	--	6.2	33	27	63
Clyde	10	DECR	5	12	--	6.8	26	32	39
Racine, Bassett	2	SIG	7	14	115	5.4	43	27	89
Oran	3	SIG	7	16	118	5.2	53	29	65
Cresco	2	DECR	6	13	--	5.3	46	34	84
Protovin	2	DECR	5	14	--	5.5	32	33	79
Lourdes	1	SIG	5	9	119	5.3	29	32	102
	1	DECR	4	11	--	5.2	24	34	70
Schley	3	SIG	7	20	101	5.4	34	26	96
Donnan	1	SIG	10	15	118	5.9	34	31	105
	2	DECR	5	10	--	5.3	25	31	96
Saude (upland)	2	SIG	11	16	84	5.6	35	18	28
Waukee (upland)	2	SIG	10	23	106	5.8	43	25	61
Sattre (upland)	1	SIG	23	43	62	5.6	75	25	62

Table 3. (Continued)

Soil group or mapping unit	No. sites	Distr. curve[b]	Soil parameter[a] PMIN (pp2m)	PMAX (pp2m)	DPMAX (cm)	PHMIN (pH)	DPHMIN (cm)	CMAX (%)	DCMAX (cm)
			Lacustrine-derived soils						
Kamrar, Guckeen	4	DECR	5	13	--	6.3	27	37	64
Marna	7	DECR	5	11	--	6.8	28	40	52
Okoboji	2	DECR	7	18	--	7.5	25	38	85
			Colluvium-derived soils (loess areas)						
Napier	6	SIG	8	12	104	6.7	29	24	44
	2	DECR	5	7	--	7.3	27	22	27
Judson, Ely (SW Iowa)	10	SIG	13	24	114	6.0	26	33	83
Judson, Ely (SE Iowa)	3	SIG	10	17	121	5.8	34	36	94
			Alluvium-derived soils (loess areas)						
Mo. bottomlands (non-calc.)	9	DECR	6	13	--	6.9	23	51	43
(calc.)	13	DECR	7	13	--	8.0	25	41	53
Harr., Wood. (local bottoms)	4	SIG	13	21	114	7.2	31	28	55
Adams, Cass, Crawford:									
Nevin	2	SIG	18	32	113	6.2	42	35	89
Bremer	1	SIG	20	24	119	6.0	32	42	90
Kennebec	3	SIG	20	37	111	6.1	60	28	91
Colo	3	SIG	27	48	112	6.0	25	37	86
Zook	2	SIG	28	60	118	6.1	38	43	103
Wabash	2	SIG	26	67	103	5.8	34	55	91
Keokuk, Musc., Wayne:									
Waukegan SiL (Terrace)	2	SIG	10	22	97	6.0	41	29	39
Whittier SiL (Terrace)	2	SIG	26	53	90	5.3	73	30	68

Table 3. (Continued)

Soil group or mapping unit	No. sites	Distr. curve[b]	Soil parameter[a] PMIN (pp2m)	PMAX (pp2m)	DPMAX (cm)	PHMIN (pH)	DPHMIN (cm)	CMAX (%)	DCMAX (cm)
Nevin	1	SIG	24	40	104	5.6	46	34	88
Canoe	1	SIG	8	46	114	5.3	25	34	80
Colo, Sawmill	4	SIG	20	42	104	6.5	38	34	82
Zook, Wabash	2	SIG	19	25	114	6.2	30	45	77
Humeston	2	SIG	18	47	111	5.4	42	41	93
Vesser	2	SIG	12	34	119	5.7	55	37	107
	Alluvium-derived soils (till areas)								
Clay, Hamilton, Lyon	8	SIG	11	17	91	6.2	25	30	49
	9	DECR	6	13	--	7.3	27	31	62
NE Iowa: Prairie	8	SIG	14	22	90	5.8	43	26	51
	2	DECR	10	18	--	5.8	63	30	58
Forest, transition	5	SIG	15	28	97	5.4	69	25	50
	Eolian LFS and FSL								
Sparta, Dickinson	8	SIG	11	17	114	5.7	54	12	49
	5	DECR	14	23	--	5.7	61	9	34
Chelsea, Lamont: EROS=1,2	5	SIG	14	31	106	5.7	58	12	52
	Loess over till units								
Sac, Primghar var.	8	DECR	5	10	--	6.6	25	36	33
Dinsdale	9	SIG	9	24	92	5.8	44	32	53
Klinger	2	SIG	12	16	64	5.9	36	31	41
	2	DECR	5	10	--	5.9	24	32	52
Clinton var.: EROS=3	3	SIG	18	40	65	5.5	38	36	33
Seymour var.	2	SIG	8	18	77	5.5	27	50	39
Marshall var.	1	SIG	10	12	77	6.2	23	33	46

P distribution, designated sigmoid (SIG) in Table 3, the STPMIN and STPMAX thus occurred in the shallower and deeper parts of the soil profile, respectively.

In many soils, the STPMAX level occurred immediately below the plow layer and the soil test P level then decreased with depth. This distribution pattern was designated decreasing (DECR) in Table 3. In these soils, STPMAX occurred in the upper part and STPMIN occurred in the lower part of the soil profile. The depth to STPMAX (DPMAX) was not computed for the soil groups with a decreasing P distribution.

The major differences among subsoil P levels and associated soil pH and clay variables of the selected soil groups will be discussed briefly in the following subsections.

<u>Deep loess-derived soils</u>

Most of the deep loess-derived soils of western Iowa were developed under the influence of prairie vegetation, but many in eastern Iowa were influenced by forest vegetation. The less PHMIN and greater DPHMIN and DCMAX in the loess-derived soils of eastern than of western Iowa (Table 3) reflect the greater degree of leaching, weathering, and degree of development in the loess soils of eastern Iowa.

The Marshall, Sharpsburg, Macksburg, and Winterset soils had the highest STPMAX values of the deep loess prairie soils in western Iowa; all of these had sigmoid P distributions with depth (Table 3). Highest levels of subsoil P (except in Macksburg) in the deep loess soils in western Iowa occurred in the Knox series (forest-prairie transition in Marshall and Monona areas). More deeply leached Moody, Galva, and

Monona soils of northwestern and western Iowa had sigmoid P distributions but their STPMAX values were only half to two-thirds of those in the Marshall and Sharpsburg soils.

All of the calcareous Ida and Dow series, about one-fourth of the Monona soils (most of which had carbonates at shallow depths), and about two-thirds of the Moody and Galva soils in Lyon County (many of which also had carbonates at shallow depths) had decreasing P distribution curves. Their STPMAX values in the upper part of the profile and their STPMIN values in the deeper profile were much lower than those in the soils with sigmoid P distributions. The more deeply leached Galva soils in northeastern Woodbury County had less PHMIN and greater STPMAX values than the Galva soils in Lyon County. The somewhat poorly drained Primghar and poorly-drained Marcus soils in Clay and Lyon counties had a decreasing P distribution curve and a very low subsoil P value in their lower profile.

The STPMAX levels were greater, the PHMIN values were less, and the DPHMIN and DCMAX values were greater in the slightly eroded than in the moderately eroded Marshall and Sharpsburg soils (Table 3). The differences due to erosion class were not as marked in the Monona and the deep-loess soils in northwestern Iowa.

The Seymour and Edina soils in southern Iowa had less STPMIN and STPMAX than the Marshall and Sharpsburg soils farther west. All of the deep loess soils in eastern Iowa except a few Taintor soils had sigmoid P distributions. The prairie Tama soils had greater STPMAX levels than the Marshall soils, but the Otley and Mahaska soils had somewhat less subsoil P than the Sharpsburg and Macksburg soils, respectively.

The dominant trend in the deep-loess soils in eastern Iowa was greater to markedly greater STPMAX levels in the forest-derived than in the prairie-derived soils (Table 3). The transition soils had intermediate STPMAX levels between the forest and prairie soils. Except in the Otley-Mahaska and Ladoga-Givin drainage sequences, the STPMAX levels were less in the somewhat poorly-drained than in the moderately well-drained soils. The poorly-drained Taintor soils had considerably less subsoil P than the somewhat poorly-drained Mahaska series. The moderately eroded soils had less STPMAX than the slightly eroded soils except in the Fayette soils in which differences were small. In most cases, the PHMIN values were greater and the DPHMIN and DCMAX values were less in the moderately eroded than in the slightly eroded soils.

Till- and lacustrine-derived soils

The till-derived soils have much less subsoil P than the loess-derived soils except those that had decreasing subsoil P levels due to higher pH levels in the deeper subsoils. Most of the till-derived soils, about 70% in the Iowan erosional surface and Kansan till areas and about 95% in the Cary till area, had decreasing P distributions and very low P levels in the deeper subsoils.

In the Kansan till area, a few of the Shelby and Adair soils had weak sigmoid P distributions. Although the PHMIN was less in the till soils in southeastern than in southwestern Iowa, the percentage of soils with sigmoid P distributions was similar in the two areas. The effect of erosion on subsoil P levels was slight in these soils.

Although the average PHMIN of the well-drained Clarion and Everly soils in the Cary till area was similar to that of the Marshall soils, most of these had decreasing P with depth because the soil pH increased rapidly below the PHMIN layer which occurred immediately below the plow layer. Most of the Nicollet and all of the Webster, Canisteo, and Harps units had decreasing P with depth. The lacustrine-derived soils in the Cary till area had similar P distributions as the till-derived soils.

Only the well-drained Ostrander and Aredale and about 30% of the moderately well-drained Kenyon soils which developed under prairie in the Iowan erosional surface had weak sigmoid P distributions (Table 3). All other prairie-derived soils in the area had decreasing P distributions. Although the Readlyn soils had the same average PHMIN as the Kenyon soils, none had a sigmoid P distribution. The PHMIN levels were higher in the Tripoli, Floyd, and Clyde series. Most of the forest-grass transition soils (Racine, Bassett, Oran, Schley, Lourdes, Donnan) had sigmoid P distributions although their STPMAX levels were considerably less than in the transition deep-loess soils. The upland outwash soils, Saude, Waukee, and Sattre, also had sigmoid P distributions.

Colluvium- and alluvium-derived soils

The colluvium-derived soils had lower STPMAX levels than their associated upland well-drained soils. Most of the Judson and Ely soils were in the Marshall area and had less STPMAX than the Marshall soils (Table 3). The Napier soils also had less subsoil P than the associated Monona soils with sigmoid P distributions. There were too few Judson and Ely profiles from eastern Iowa to compare with their associated upland soils.

Most of the alluvium-derived soils in the loess areas had sigmoid P distributions (Table 3). The soils in the Missouri River bottomland area, however, had decreasing P distributions with depth. Most of these soils had high pH levels or were calcareous in the subsoil. The Kennebec and Colo soils in the local stream bottomlands in Harrison and Woodbury counties had lower subsoil P levels and higher PHMIN levels than those farther east.

In Adams, Cass, and Crawford counties, the silty terrace units (Nevin and Bremer) had subsoil P levels similar to those of the upland soils, but the bottomland soils had higher subsoil P levels than the upland soils. In this area, STPMAX also increased as drainage became poorer from the moderately well-drained Kennebec, to the poorly-drained Colo and Zook, and to the very poorly-drained Wabash series.

The alluvial soils in the loess areas in eastern Iowa that developed under prairie had somewhat less subsoil P than those in western Iowa. They had higher STPMIN levels but similar STPMAX levels as the associated prairie upland soils. The poorly-drained Colo and Sawmill soils and the poorly-drained to very poorly-drained Zook, Humeston, and Wabash soils, however, had similar STPMAX values. The transition Whittier and Canoe soils on terrace positions had higher STP levels than the prairie Waukegan SiL and Nevin soils due to forest influence.

The alluvium-derived soils in the till areas had less subsoil P than those in the loess areas but more than the associated upland soils

(Table 3). About 80% of these units in northeastern Iowa, but only about 50% of them in central and northwestern Iowa, had sigmoid P distributions. Those with sigmoid distributions in northwestern Iowa were the well-drained Wadena (moderately deep and deep) and Dempster units on terrace positions. The others with decreasing P levels generally had higher PHMIN levels or were calcareous. Most of the alluvium soils in northeastern Iowa were on terrace positions; several had higher subsoil P levels because of forest influence.

Eolian and loess over till soils

The eolian sands in northeastern Iowa had higher subsoil P levels than the associated till soils; most had sigmoid P distributions. The forested Chelsea LFS and Lamont FSL soils had sigmoid P distributions and higher STPMAX levels than the prairie-derived Sparta LFS and Dickinson FSL soils.

The shallow loess units (51-102 cm or 20-40 in. of loess over till) usually had lower subsoil P levels than the associated deep loess-derived soils (Table 3). The depth to STPMAX was also less in these units than in the deep-loess units.

Correlation Analysis of Subsoil P and Soil, Location, and Climatic Variables

The symbols, identifications, means, and ranges (minimum and maximum values) of the variables that were used in the correlation and multiple regression analysis are listed in Table 4; the variables included in the simple correlation analysis are listed in Table 5. The simple correlations between these variables were computed and used as guidance for

Table 4. Symbols, identification, means, and ranges of the variables used in the correlation and regression analyses

Symbol	Variable[a]	Col. no. on new data card	Mean	Range
DEPTH	Depth to the mid-point of each horizon sampled, cm, but later transformed to meters for MODELS G to P	5-7	66.3	15-137
GHP	Genetic horizon for STP regressions, coded 00 to 80	8-9	35.3	0-80
GHK	Genetic horizon for STK, PH regressions, coded 20 to 80	10-11	46.3	20-80
PH	Soil pH, coded pH - 4.5	12-14	2.19	0.4-3.8
STP	Soil test P (pp2m)	15-17	15.0	4-99
STK	Soil test K (pp2m)	18-20	48.6	10-370
SAND	Sand (%)	21-22	19.5	1-95
SILT	Silt (%)	23-24	51.8	1-81
CLAY	Clay (%)	25-26	28.7	3-61
OC	Organic carbon (%)	27-29	0.70	0.0-4.3
BD	Bulk density, coded (BD-1.00)*100	30-31	40.9	18-81
PEDISED	Pedisediment, sediment over till, lacustrine	32	0.150	0-1
TILL	Till, paleosol	33	0.191	0-1
COLLUV-L	Colluvium below loess soils	34	0.030	0-1
ALLUV-L	Alluvium (loess areas)	35	0.075	0-1
ALLUV-T	Alluvium (till areas)	36	0.046	0-1
EOLIAN	Eolian LFS and FSL	37	0.024	0-1
TWP	Township no. (S-N direction), coded TWP-65	38-39	19.6	2-35
RANGE	Range no. (E-W direction)	40-42	25.0	0-48

[a]More information about the variables is given in Appendix Tables A1, A2, and A3.

Table 4. (Continued)

Symbol	Variable	Col. no. on new data card	Mean	Range
SLOPE	Slope of site (%)	43-44	4.4	0-20
SLCONF	Slope configuration, coded 1 to 6	45	3.1	1-6
EROS	Erosion class, coded 0 to 3	46	0.72	0-3
THAHOR	Thickness of A horizon, cm	47-49	34.1	0-109
DRAIN	Internal drainage class, coded 10 to 90	50-51	43.9	10-85
BIO	Biosequence, coded 1 to 5	52	4.60	1-5
DCAL	Depth to top of cal. hor., coded: 152-depth, cm	53-55	29.6	0-137
PHMIN	Minimum pH, coded PHMIN = pH - 4.5	56-58	1.71	0.4-3.6
DPHMIN	Depth to midpoint of PHMIN layer, cm	59-61	32.5	15-94
CMAX	Maximum clay in the subsoil (%)	62-63	33.2	4-61
DCMAX	Depth to midpoint of CMAX layer, cm	64-66	52.3	18-122
PPT	Annual precipitation, coded: ppt. - 63.0, cm	67-70	17.03	0.2-26.2
TEMP	Annual temperature, coded: temp. - 7.0, °C	71-74	2.01	0.2-3.8
PE	Annual potential evapotranspiration, coded: PE - 62.0, cm	75-78	5.23	0.6-8.9

Table 5. Variables included in the correlation analysis of the soil, location, and climatic variables

X_i	Variable	X_i	Variable	X_i	Variable
1	DEPTH	12	PEDISED	23	THAHOR
2	GHP	13	TILL	24	DRAIN
3	GHK	14	COLLUV-L	25	BIO
4	PH	15	ALLUV-L	26	DCAL
5	STP	16	ALLUV-T	27	PHMIN
6	STK	17	EOLIAN	28	DPHMIN
7	SAND	18	TWP	29	CMAX
8	SILT	19	RANGE	30	DCMAX
9	CLAY	20	SLOPE	31	PPT
10	OC	21	SLCONF	32	TEMP
11	BD	22	EROS	33	PE

variable selection in the STP multiple regression analysis.

Correlation coefficients greater than ± 0.39 between the STP, soil, location, and climatic variables are given in Table 6. Most of the r-values in these data from all horizons in the profile were similar to those reported previously (Salih, 1979) which were determined from two fixed layer or depths in the profile. If the r-values between variables in the upper and lower parts of the profile varied considerably in the previous study, the ones in this study were close to their average values.

The dependent variable, STP, was most highly correlated with BIO (biosequence) as was reported previously by Salih (1979). The only other variables that had some correlation with STP were genetic horizon coded for STP regressions (GHP) and depth to minimum pH (DPHMIN). The DEPTH

Table 6. Simple correlation coefficients greater than ±0.39 between soil test P, soil, location, and climatic variables

Between variables		r	Between variables		r
STP and	GHP	.41	BD and	TILL	.72
	BIO	-.51		RANGE	-.46
	DPHMIN	.41			
			TWP and	CMAX	-.45
DEPTH and	GHP	.47		PPT	-.55
	GHK	.79		TEMP	-.96
	OC	-.67		PE	-.96
	BD	.49			
			RANGE and	DCAL	.48
GHP and	OC	-.42		PHMIN	.58
	DCAL	-.53		DPHMIN	-.48
	PHMIN	-.40		PPT	-.85
GHK and	PH	.50	SLOPE and	SLCONF	-.54
	OC	-.71		EROS	.70
				THAHOR	-.57
PH and	RANGE	.51		DRAIN	-.46
	DCAL	.72			
	PHMIN	.79	SLCONF and	EROS	-.64
	DPHMIN	-.44		THAHOR	.68
	PPT	-.53		DRAIN	.52
STK and	ALLUV-L	.48	EROS and	THAHOR	-.80
	RANGE	.45		DRAIN	-.40
SAND and	SILT	-.90	THAHOR and	DRAIN	-.40
	CLAY	-.56			
	BD	.70	DRAIN and	CMAX	.63
	TILL	.41			
	EOLIAN	.44	BIO and	DPHMIN	-.44
	CMAX	-.48			
	TEMP	-.43	DCAL and	PHMIN	.75
	PPT	-.42		PPT	-.55
SILT and	BD	-.77	PHMIN and	PPT	-.59
	TILL	-.50			
	RANGE	.41	CMAX and	TEMP	.44
				PE	.44
CLAY and	DRAIN	.55			
	CMAX	.83	PPT and	TEMP	.44
				PE	.41
OC and	BD	-.42			
	THAHOR	.46	TEMP and	PE	.99

variable (depth to the midpoint of each horizon) which was added for this study to describe the subsoil P distribution in the profile had no correlation with STP. This was expected because about 40% of the profiles had decreasing STP with depth (negative correlation) and the rest had a sigmoid (increasing) distribution with depth (positive correlation).

The DEPTH variable had a moderately high correlation with GHP (r = 0.47); GHP is the coded genetic horizon for STP regressions for which all calcareous horizons were coded 0. DEPTH, however, had a high correlation with GHK (r = 0.79); GHK is the coded genetic horizon for STK regressions for which the calcareous C horizons were coded 80, the same coding as for noncalcareous C horizons. This latter correlation showed that, except for the calcareous horizons, the correlation between DEPTH and GHP would also be high. Because of the high correlations between DEPTH and GHP in most genetic horizons, the GHP variable was deleted from most of the regressions after the initial analysis. It was added in the last series of regressions, however, to improve the prediction value (higher R^2) of the STP multiple regressions with soil horizon variables deleted.

The DEPTH variable also had a high correlation (r = -0.67) with OC (percentage organic carbon content of each horizon). This was expected because the OC content decreases with depth in practically all soils.

The simple correlations between the rest of the variables in Table 6 can best be summarized by showing the correlations between variables within related groups in Table 7. In the soil pH-related variables

Table 7. Simple correlation coefficients between variables within related groups[a]

Variable	Soil pH-related variables						
	GHP	PH	RANGE	DCAL	PHMIN	DPHMIN	PPT
GHP	—	—	—	-.53	-.40	—	—
PH		—	.51	.72	.79	-.44	-.53
RANGE			—	.48	.58	-.48	-.85
DCAL				—	.75	—	-.55
PHMIN					—	—	-.59
DPHMIN						—	—

Variable	Texture-related variables						
	SAND	SILT	CLAY	BD	TILL	DRAIN	CMAX
SAND	—	-.90	-.56	.70	.41	—	-.48
SILT		—	—	-.77	-.50	—	—
CLAY			—	—	—	.55	.83
BD				—	.72	—	—
TILL					—	—	—
DRAIN						—	.63

Variable	Organic matter-related variables					
	OC	SLOPE	SLCONF	EROS	THAHOR	DRAIN
OC	—	—	—	—	.46	—
SLOPE		—	-.54	.70	-.57	-.46
SLCONF				-.64	.68	.52
EROS				—	-.80	-.40
THAHOR					—	-.40

Variable	Location and climatic variables				
	TWP	RANGE	PPT	TEMP	PE
TWP	—	—	-.55	-.96	-.96
RANGE		—	-.85	—	—
PPT			—	.44	.41
TEMP				—	.99

[a]Only the r-values greater than ±0.39 are shown.

which included RANGE (E-W direction) and PPT (average annual precipitation), very high correlations occurred between PH (pH of each horizon) and DCAL (coded depth to calcareous horizon) (r = 0.72), PH and PHMIN (minimum pH in the subsoil) (r = 0.79), and DCAL and PHMIN (r = 0.75). The high correlation between RANGE and PPT will be discussed later. PHMIN had moderately-high correlations with both RANGE and PPT. Some of the other variables were moderately correlated.

In the texture-related groups of variables (Table 7), high to very high correlations greater than ±0.60 occurred between SAND (% sand) and SILT (% silt), SAND and BD (bulk density of the horizon), SILT and BD, CLAY (% clay) and CMAX (maximum clay in the profile), BD and TILL (till parent material), and DRAIN (coded drainage class) and CMAX. Some other variables were moderately correlated.

In the organic matter-related group (Table 7), high to very high correlations greater than ±0.60 occurred between SLOPE (% slope of the site) and EROS (coded erosion class), SLCONF (coded slope configuration) and EROS, SLCONF and THAHOR (thickness of A horizon), and EROS and THAHOR. Other variables were moderately correlated.

The climatic variables of PPT, TEMP (mean annual temperature), and PE (potential annual evapotranspiration) were added to this study to determine if these causative variables on soil profile development would be more useful to explain STP variation than the location variables of TWP (S-N direction) and RANGE (E-W direction). The very high correlations between TWP and both TEMP and PE (r = -0.96) and between RANGE and PPT (r = -0.85) in Table 7 showed that either the location or the climatic variables, but not both sets, could be included in the regression models.

The near-perfect correlation between TEMP and PE of 0.99 was expected because Thornthwaite (1948) had reported a linear relationship between the logarithms of temperature and unadjusted PE. Even after the adjustments for day and month length, one would expect a high correlation between the two over a relatively small geographical area. The PE variable then was deleted from all models after the first one because the TEMP variable was more accurately estimated than the PE variable.

Several of the correlation coefficients between variables shown in Tables 6 and 7 were high enough to cause distortion of the regression coefficients and interference in the interpretation of the variable effects on STP if the highly-correlated variables were included in the regression model (Henao, 1976; Pena-Olvera, 1979).

A few variables were very highly correlated (above about ±0.75). Usually, only one of the highly correlated pair of variables is retained in multiple regression analysis; because this variable explains most of the effect of the other one, little gain in R^2 occurs when both are included. These variables are: PH and PHMIN, DCAL and PHMIN, SAND and SILT, SILT and BD, CLAY and CMAX, and EROS and THAHOR. The very high correlations between TWP and TEMP, RANGE and PPT, and TEMP and PE were discussed previously.

The variables that had correlation coefficients above ±0.60 but less than ±0.75 were also involved in the model selections to exclude all variables that were correlated greater than ±0.60. These included: DEPTH and OC, PH and DCAL, SAND and BD, BD and TILL, DRAIN and CMAX, SLOPE and EROS, SLCONF and EROS, and SLCONF and THAHOR. The techniques of selecting the more important of two highly correlated variables from alternative models were explained by Salih (1979).

One cannot have all the three textural variables (SAND, SILT, and CLAY) in the same model. Because the sum of the three = 100, it is possible to predict one of the textural variables from the other two without error. Hence, this causes a singularity in the data matrix, which, in turn, makes the estimation of the regression coefficients impossible (Salih, 1979). So, only SAND and CLAY can be included in one model and SILT and CLAY in an alternate model.

Multiple Regressions of STP on Linear, Quadratic, and Cubic Functions of Selected Variables, MODELS A to F Series

A multiple regression of STP was initially computed on the quadratic functions of all variables except for linear functions of the parent material variables (which were dummy or linear variables) and the cubic function of the DEPTH variable. The cubic function of DEPTH was included to explain the sigmoid STP distributions observed particularly in the more developed loess-derived soils.

Different regressions were selected for varying degrees of correlation between the variables, as follows: (1) high correlations disregarded (MODELS A and B series) and (2) no variables included which were correlated greater than ±0.60 (MODELS C and D series). This technique was used by Salih (1979) previously.

The relative effects of the climatic (PPT and TEMP) and the location (TWP and RANGE) variables on STP were compared in alternate parallel models. The climatic variables were included in MODELS A, C, and E series. The location variables were included in the alternate MODELS B, D, and F series.

To determine how well STP could be predicted in the absence of the soil horizon variables, these variables were deleted in the MODELS E and F series. The soil horizon variables are the costly and time-consuming ones to determine or estimate accurately. Salih (1979) had investigated the effects of deleting the soil horizon variables on prediction of STP in a series of regression models. Although deletion of these variables reduced the R^2-values by about 0.04, he concluded that STP still could be estimated with good precision if they were not included.

Additional regression models also were computed in the MODELS C to F series to determine the value of the GHP variable for predicting STP. It was intercorrelated with DEPTH and other variables and appeared to complicate interpretation of the effects of some variables on STP.

<u>Multiple regressions of STP on all variables, MODELS A and B series</u>

<u>Model selection</u> The initial regression of STP (MODEL A-1) on the linear functions of the parent material variables, cubic function of the DEPTH variable, and quadratic functions of all other variables except GHK and SILT included 55 variates (Table 8) and had an R^2 of 0.638 (Table 9). To test the effect of all location and climatic variables on STP, the TWP, RANGE, PPT, TEMP, and PE variables were deleted in MODEL A-2. The R^2 was decreased about 0.02 from that in MODEL A-1 (Table 9).

To MODEL A-2, the climatic variables of PPT and TEMP were added in MODEL A-3 which then was used as the base model for obtaining the final

Table 8. Variables included in the multiple regressions of STP on the linear, quadratic, and cubic functions of selected variables, MODELS A to F series

X_i	Variate	X_i	Variate	X_i	Variate
1	DEPTH	21	SLCONF	42	$SILT^2$
2	GHP	22	EROS	43	$CLAY^2$
3	GHK	23	THAHOR	44	OC^2
4	PH	24	DRAIN	45	BD^2
5	STP[a]	25	BIO	46	TWP^2
6	STK	26	DCAL	47	$RANGE^2$
7	SAND	27	PHMIN	48	$SLOPE^2$
8	SILT	28	DPHMIN	49	$SLCONF^2$
9	CLAY	29	CMAX	50	$EROS^2$
10	OC	30	DCMAX	51	$THAHOR^2$
11	BD	31	PPT	52	$DRAIN^2$
12	PEDISED	32	TEMP	53	BIO^2
13	TILL	33	PE	54	$DCAL^2$
14	COLLUV-L	34	$DEPTH^2$	55	$PHMIN^2$
15	ALLUV-L	35	$DEPTH^3$	56	$DPHMIN^2$
16	ALLUV-T	36	GHP^2	57	$CMAX^2$
17	EOLIAN	37	GHK^2	58	$DCMAX^2$
18	TWP	38	PH^2	59	PPT^2
19	RANGE	40	STK^2	60	$TEMP^2$
20	SLOPE	41	$SAND^2$	61	PE^2

[a]STP is the dependent (Y) variable.

model in the MODEL A series. The PE variable was not included because of its very high correlation with TEMP, as discussed previously. The TWP and RANGE variables were added to MODEL A-2 to get MODEL B-3 which was then used as the base model for the MODEL B series. In the selection of the final models in both the MODELS A and B series, the high correlations between variables were disregarded.

The squared variates and the $DEPTH^3$ variate were next deleted in MODELS A-4 and B-4 to determine the effects of these variates on the

Table 9. Model selection steps, MODELS A and B series

Model no.	No. of X variates	Model selection steps	R^2
A-1	55	Complete prediction model, all variates listed in Table 8 except GHK, SILT, GHK^2, and $SILT^2$	.6384
2	45	Deleted location (TWP and RANGE) and climatic (PPT, TEMP, and PE) variables from MODEL A-1	.6167
3	49	Alternate model; added PPT, PPT^2, TEMP and $TEMP^2$ variates to MODEL A-2	.6306
4	27	Linear model, deleted all squared variates and $DEPTH^3$ from MODEL A-3	.5791
6	40	Deleted ns variates of GHP^2, STK^2, $SAND^2$, $SLCONF^2$, $EROS^2$, $THAHOR^2$, $DPHMIN^2$, $CMAX^2$, and $DCMAX^2$ stepwise from MODEL A-3	.6301
8	37	Final complete prediction model; deleted ns variates of SLCONF, CMAX, and PH^2 stepwise from MODEL A-6	.6295
9	36	Deleted $DEPTH^3$ from MODEL A-8	.6293
B-3	49	Alternate model; added TWP, TWP^2, RANGE, and $RANGE^2$ variates to MODEL A-2	.6257
4	27	Linear model, deleted all squared variates and $DEPTH^3$ from MODEL B-3	.5741
7	40	Deleted ns variates of GHP^2, STK^2, $SAND^2$, $SLCONF^2$, $EROS^2$, $THAHOR^2$, $DPHMIN^2$, $CMAX^2$, and $DCMAX^2$ stepwise from MODEL B-3	.6252
9	37	Final complete prediction model; deleted ns variates of SLCONF, CMAX, and PH^2 stepwise from MODEL B-7	.6247
10	36	Deleted $DEPTH^3$ from MODEL B-9	.6243

predictions of STP. The R^2-values in both models were decreased about 0.05 (5%) from those of MODELS A-3 and B-3 (Table 9).

The nonsignificant variates were then deleted stepwise as described in Table 9 to get the final complete prediction models, MODELS A-8 and B-9, each with 37 variates. The R^2-values for MODELS A-8 and B-9 were 0.630 and 0.625, respectively. The slightly higher R^2 of MODEL A-8 than of MODEL B-9 indicated that the climatic variables are slightly better than the location variables for estimating the STP levels. In an additional model in each series, deletion of the $DEPTH^3$ variate, significant at the 5% level, decreased R^2 very slightly (Table 9).

Effects of selected variables on STP The regression coefficients for the variates retained in the final complete prediction MODELS A-8 and B-9 are given in Table 10. The signs of all corresponding variates were the same in both final models except for the nonsignificant DCAL variate. The significances and magnitudes of most corresponding variates were also similar in both models. Only the ALLUV-T, linear BD, and $SLOPE^2$ variates were more significant in MODEL A-8 (with PPT and TEMP) than in MODEL B-9 (with TWP and RANGE). The magnitudes of the regression coefficients of corresponding variates differed more than 30% only for the STK, SAND, BD, and DCAL variates (Table 10). These slight differences may be due to differences in the interactions between these variables and the climatic and location variables.

Two of the variables highly correlated with others, CMAX and SLCONF, were deleted in both model series because of nonsignificance; both then were omitted from subsequent models. All other highly correlated variables had highly significant effects on STP and need to be tested in alternate models in the next series of regressions.

Table 10. Regression statistics of STP on all variates, disregarding correlations between variables, MODEL A-8 (with PPT and TEMP) and MODEL B-9 (with TWP and RANGE)

X_i	Variable	Regression coefficients (b_i)			
		MODEL A-8		MODEL B-9	
		Linear	Squared	Linear	Squared
1,34	DEPTH[a]	-0.111	0.00311**	-0.101	0.00316**
2	GHP	0.103**	—	0.103**	—
4	PH	-4.883**	—	-4.935**	—
6	STK	0.0143**	—	0.0217**	—
7	SAND	0.0673**	—	0.0895**	—
9,43	CLAY	0.944**	-0.0125**	0.953**	-0.0129**
10,44	OC	-5.135**	2.388**	-4.992**	2.302**
11,45	BD	0.294**	-0.00571**	0.139++	-0.00472**
12	PEDISED	-5.18**	—	-4.39**	—
13	TILL	-5.65**	—	-4.36**	—
14	COLLUV-L	-6.59**	—	-6.41**	—
15	ALLUV-L	5.91**	—	6.29**	—
16	ALLUV-T	-2.80**	—	-2.25*	—
17	EOLIAN	-12.71**	—	-12.42**	—
18,46	TWP	—	—	0.235**	-0.00619**
19,47	RANGE	—	—	0.287**	-0.00874**
20,48	SLOPE	0.338*	-0.0232**	0.309*	-0.0187*
22	EROS	0.915**	—	0.846**	—
23	THAHOR	0.104**	—	0.101**	—
24,52	DRAIN	-0.811**	0.00723**	-0.799**	0.00703**
25,53	BIO	-14.19**	1.404**	-14.24**	1.411**
26,54	DCAL	0.000085	0.000483**	-0.0160+	0.000608**
27,55	PHMIN	8.784**	-2.016**	10.850**	-2.485**
28	DPHMIN	0.137**	—	0.135**	—
30	DCMAX	0.0163*	—	0.0193*	—
31,59	PPT	1.025**	-0.0222**	—	—
32,60	TEMP	2.180*	-0.787**	—	—
	Intercept	27.29**		36.82**	
	R^2	0.630**		0.625**	

[a]Regression coefficients for $DEPTH^3$ (X35) were -0.0000114* and -0.0000117* in MODELS A-8 and B-9, respectively.

**,*,++,+Significant at the 1%, 5%, 10%, and 15% levels, respectively, in this and all other tables.

The effects of the variables on STP will be discussed briefly; detailed discussion of their effects will be presented in the next sections using the final reduced prediction models of MODELS C and D for all variables and MODEL E for all variables except the horizon variables.

The effects of the selected variables on STP can be obtained from the regression coefficients of the final models in Table 10. For the linear functions of the variables, the linear coefficients in Table 10 give the direction and rate of change (slope) of STP per unit change of the variable over the relevant range. For the quadratic and cubic functions, the partial derivative gives the rate of change (slope) of STP per unit change of the variable. The slope varies at any point on the curvilinear function of STP on the variable, depending on the selected level of the variable.

The value or level of the variable associated with minimum or maximum STP in a quadratic function also can be computed from the partial derivative, as described in the Materials and Methods chapter. For example, the partial derivative of STP with respect to CLAY (MODEL A-8, Table 10) is 0.9444 - 0.0250 CLAY. Setting the partial derivative equal to 0 and solving shows that maximum STP occurred at 37.8% clay. The values of the DEPTH variable associated with both a minimum and maximum STP in the cubic function also can be computed from the partial derivative as described in the Methods and Materials chapter.

The linear effects of the variables on STP (Table 10) showed that GHP, STK, SAND, ALLUV-L, EROS, THAHOR, DPHMIN, and DCMAX had positive effects on STP; PH and all other parent material variables had negative effects. These effects were similar to those reported by Salih (1979), except for SAND (nonsignificant) and EROS which had a negative effect on STP. Because all variables were included in these models, the effect of EROS appears distorted because of its high correlations with SLOPE and THAHOR (Table 7).

For the quadratic functions of the variables and the cubic function of DEPTH, the computed values of the variables associated with maximum or minimum STP, or both for DEPTH, are given in Table 11 for both MODELS A-8 and B-9. The values of DEPTH at minimum and maximum STP were 18-20 cm and 162 cm deep, respectively. The curvilinear effects of the other variables, except OC and DCAL, on STP were similar to those reported by Salih (1979). The levels of PPT and TEMP associated with maximum STP were those associated with the RANGE and TWP locations, respectively, where maximum STP occurred. The decreasing effect of OC on STP at OC levels from 0 to 1.08% and increasing STP as depth to the calcareous horizon decreased were unexpected. These effects probably are due to the high correlations with other variables included in the final models.

In summary, the climatic variables of PPT and TEMP were slighly better (higher R^2) for predicting STP than the location variables of TWP and RANGE. However, either group can be used in regression models in Iowa because PPT and RANGE and TEMP and TWP are highly correlated. The effects of most variables on STP were as expected. The effects of a few on STP were different from expected probably because of distortion of their regression coefficients in the presence of highly correlated

Table 11. Computed values of the variables associated with maximum or minimum STP, MODELS A-8 and B-9

Variable	MODEL A-8		MODEL B-9	
	STPMAX or STPMIN	Value	STPMAX or STPMIN	Value
DEPTH[a]	MIN MAX	20 cm (8 in.) 162 cm (64 in.)	MIN MAX	18 cm (7 in.) 162 cm (64 in.)
CLAY	MAX	37.8% clay	MAX	37.2% clay
OC	MIN	1.08% OC	MIN	1.08% OC
BD	MAX	26; decoded = 1.26 g/cm^3	MAX	15; decoded = 1.15 g/cm^3
TWP	--	--	MAX	19; decoded = TWP 84
RANGE	--	--	MAX	RANGE 16
SLOPE	MAX	7.3%	MAX	8.3%
DRAIN	MIN	56; somewhat poor to poor	MIN	57; somewhat poor to poor
BIO	MIN	5.0; prairie	MIN	5.0; prairie
DCAL	Increasing at an increasing rate of coded DCAL		MIN	13; decoded = 139 cm to carbonate layer
PHMIN	MAX	2.2; decoded = pH 6.7	MAX	2.2; decoded = pH 6.7
PPT	MAX	23; decoded = 86 cm (34 in.)	--	--
TEMP	MAX	1.4; decoded = 8.4°C (47.2°F)	--	--

[a]In MODELS A-9 and B-10 from which DEPTH^3 was deleted, the regression coefficients were positive for both DEPTH and DEPTH^2; in these models, STP was increasing at an increasing rate with increasing DEPTH.

variables. This effect has been reported previously by several researchers.

Multiple regressions of STP on all variables, MODELS C and D series

The first objective of the MODELS C and D series was to develop final reduced prediction models with no variables correlated greater than ±0.60. This was done to avoid the distortion of regression coefficients which can occur if highly correlated variables are included in the same regressions, as in the MODELS A and B series. The reduced prediction models were selected by testing the variables that had correlation coefficients above ±0.60 in alternate models. The correlated variable that had less effect on R^2 was deleted and the other was retained.

The second objective was to test further the relative effects of the climatic and the location variables on STP. These variables were compared in alternate parallel models of the MODEL C series (climatic variables of PPT and TEMP) and MODEL D series (location variables of TWP and RANGE).

The third objective was to determine the effects of the GHP variable on STP in both series of models. Final reduced prediction models were also developed without the GHP variable.

Model selection The initial regression of STP (MODEL C-1) included the linear functions of the parent material variables, cubic function of the DEPTH variable, and quadratic functions of all other variables except GHK, SILT, TWP, and RANGE (Table 8). This model, the same as MODEL A-3, had an R^2 of 0.631 and included 49 variates (Table 12).

Table 12. Model selection steps, MODELS C and D series

Model no.	No. of X variates	Model selection steps	R^2
C- 1	49	Same as MODEL A-3; PPT and TEMP included but TWP and RANGE deleted	.6306
2	43	Deleted OC, SLCONF, and CMAX variables from MODEL C-1; this was the base model	.6257
3 to 12	39 to 43	Tested correlated variables of PH, DCAL, PHMIN, SAND, SILT, BD, TILL, SLOPE, EROS, and THAHOR in alternate models by deleting 1 or 2 variables from MODEL C-2; PH, BD, SLOPE, and THAHOR variables were retained	.6269 to .6092
13 to 17	34 to 27	Deleted SAND, TILL, EROS, DCAL, and PHMIN variables from MODEL C-2 and then nonsignificant variates stepwise from MODEL C-13; MODEL C-17 was final reduced prediction model (no variables correlated >±0.60)	.6134 to .6129
18	26	Deleted $DEPTH^3$ from MODEL C-17	.6119
19 to 23	32 to 25	Deleted GHP and GHP^2 from MODEL C-13 and then ns variates stepwise from MODEL C-19; MODEL C-23 was final reduced prediction model with GHP variable deleted	.6056 to .6050
24	24	Deleted $DEPTH^3$ from MODEL C-23	.6036
D- 1	49	Same as MODEL B-3; TWP and RANGE included, PPT and TEMP deleted	.6257
17	27	Deleted same variates as were deleted from MODELS C-1 to C-17; MODEL D-17 was final reduced prediction model	.6080
18	26	Deleted $DEPTH^3$ from MODEL D-17	.6072
19 to 22	32 to 25	Deleted GHP and GHP^2 and the ns variates stepwise from MODEL D-13; MODEL D-22 was final reduced prediction model with GHP variable deleted	.6010 to .6006
23	24	Deleted $DEPTH^3$ from MODEL D-22	.5994

In MODEL C-2, the OC variable which was highly correlated with DEPTH and the SLCONF and DCMAX variables which were not significant in the MODEL A series were deleted from MODEL C-1. MODEL C-2 then was used as the base model for the next model selection steps.

In MODELS C-3 to C-12 (Table 12), variables correlated greater than ±0.60 were tested in alternate models by deleting one or more of the correlated variables from the base model, MODEL C-2. The ones that gave higher R^2-values were retained and the others were deleted. Variables retained in MODEL C-13 were PH, BD, SLOPE, and THAHOR and those deleted were SAND, TILL, EROS, DCAL, AND PHMIN.

Next, the nonsignificant variates of ALLUV-T, SLOPE, DCMAX, STK^2, $SLOPE^2$, $DPHMIN^2$, and $DCMAX^2$ were deleted stepwise from MODEL C-13. MODEL C-17 was the final reduced prediction model (no variables correlated >±0.60). Although the variates were reduced from 43 in MODEL C-2 to 27 in MODEL C-17, the R^2-value was only reduced from 0.626 to 0.613 (Table 12). Very little reduction in R^2 resulted from deletion of the $DEPTH^3$ variate in MODEL C-18.

To develop the reduced prediction model without the GHP variable, the GHP variable was deleted in MODEL C-19 from MODEL C-13; then, the same nonsignificant variates that were deleted in MODELS C-14 to C-17 were deleted stepwise in MODELS C-20 to C-23 (Table 12). MODEL C-23 was the final reduced prediction model without the GHP variable. The R^2 was reduced from 0.613 in MODEL C-17 to 0.605 in MODEL C-23 by deleting the GHP variable.

The initial model for the MODEL D series (MODEL D-1) was the same as

MODEL C-1 except that the climatic variables were deleted and the location variables of TWP and RANGE were included. The model selection steps for the MODEL D series were identical to those of the MODEL C series (Table 12). Deletion of the GHP variable reduced the R^2 from 0.608 in MODEL D-17 to 0.601 in MODEL D-22.

The R^2-values for the final reduced prediction models with the GHP variable, MODELS C-17 (with climatic variables) and D-17 (with location variables), were 0.613 and 0.608, respectively. Without the GHP variable, the R^2-values of MODELS C-23 and D-22 were 0.605 and 0.601, respectively. The slightly higher R^2-values of the MODEL C series than those of the corresponding MODEL D series indicated that the climatic variables were again slightly better than the location variables for predicting STP levels. Also, the deletion of the $DEPTH^3$ variate in both series caused very little reduction in R^2 values (Table 12).

Because the pH variable (pH of the soil horizon) identified the calcareous horizon in these all-variable models, the deletion of the GHP variable in both series caused only slight reductions in R^2. The GHP variable was tested because of its high correlation with DEPTH in all horizons excluding the calcareous horizons.

Effect of selected variables on STP The regression statistics of the final reduced prediction models without the GHP variable, MODELS C-23 and D-22, are given in Table 13. All variables had similar effects on STP in both models except STK and BD which had somewhat different effects. For the variables that had quadratic or cubic effects on STP, the values of these variables associated with maximum or minimum STP

Table 13. Regression statistics of STP on selected variates, final reduced prediction models (no variables correlated greater than ±0.60), MODELS C-23 and D-22

X_i	Variable	Regression coefficients (b_i)			
		MODEL C-23		MODEL D-22	
		Linear	Squared	Linear	Squared
1,34	DEPTH[a]	-0.183*	0.00512**	-0.144++	0.00469**
4,38	PH	4.71**	-1.997**	5.61**	-2.187**
6	STK	0.0193**	—	0.0257**	--
9,43	CLAY	0.627**	-0.00907**	0.608**	-0.00926**
11,45	BD	0.294**	-0.00663**	0.194**	-0.00568**
12	PEDISED	-1.57**	—	-1.34**	—
14	COLLUV-L	-6.61**	—	-6.33**	--
15	ALLUV-L	6.38**	—	6.72**	--
17	EOLIAN	-9.13**	—	-9.57**	—
18,46	TWP	—	—	0.250**	-0.00638**
19,47	RANGE	--	—	0.261**	-0.00757**
23,51	THAHOR	-0.0521++	0.000940**	-0.0510++	0.000916**
24,52	DRAIN	-0.806**	0.00733**	-0.829**	0.00747**
25,53	BIO	-15.22**	1.537**	-15.19**	1.542**
28	DPHMIN	0.141**	—	0.139**	--
31,59	PPT	0.877**	-0.0200**	—	--
32,60	TEMP	2.061*	-0.713**	--	--
Intercept		43.3**		51.1**	
R^2		0.605**		0.601**	

[a]Regression coefficients for $DEPTH^3$ were -0.0000207** and -0.0000192** for MODELS C-23 and D-22, respectively.

are shown in Table 14 for both MODELS C-23 and D-22. The effects of the variables on STP will be discussed in the following subsections.

DEPTH The partial derivative of STP with respect to DEPTH in MODEL C-23 (Table 13) is dSTP/dDEPTH = -0.183 + 0.01024 DEPTH -

Table 14. Computed values of the variables associated with maximum or minimum STP, MODELS C-23 and D-22

Vari-able	MODEL C-23 STPMAX or STPMIN	MODEL C-23 Value	MODEL D-22 STPMAX or STPMIN	MODEL D-22 Value
DEPTH	MIN MAX	20 cm (8 in.) 145 cm (57 in.)	MIN MAX	17 cm (7 in.) 146 cm (57 in.)
PH	MAX	1.2; decoded = pH 5.7	MAX	1.3; decoded = pH 5.8
CLAY	MAX	34.6% clay	MAX	32.8% clay
BD	MAX	22; decoded = 1.22 g/cm^3	MAX	17; decoded = 1.17 g/cm^3
TWP	—	—	MAX	20; decoded = TWP 85N
RANGE	—	—	MAX	17; RANGE 17W
THAHOR	MIN	27.7 cm (11 in.)	MIN	27.8 cm (11 in.)
DRAIN	MIN	55; decoded = somewhat poor to poor	MIN	55; decoded = somewhat poor to poor
BIO	MIN	4.9; decoded = prairie	MIN	4.9; decoded = prairie
PPT	MAX	22; decoded = 85 cm (33.5 in.)	—	—
TEMP	MAX	1.4; decoded = 8.4°C (47.1°F)	—	—

0.0000621 $DEPTH^2$. To calculate the DEPTH values associated with minimum STP (STPMIN) and maximum STP (STPMAX) in the cubic function, the partial derivative is set = 0 and then solved using the quadratic formula, DEPTH = $[-b \pm (b^2 - 4ac)^{1/2}]/2a$, where a = coefficient of the squared term, b = coefficient of the linear term, and c = constant. The two values of DEPTH = 20.4 cm (8 in.) and 144.5 (57 in.) were those associated with STPMIN and STPMAX, respectively.

The effect of increasing depth on change in STP (ΔSTP) in MODEL C-23 is shown in Figure 6. The ΔSTP with increasing depth is computed from the cubic function of the DEPTH variable in MODEL C-23 (Table 13), as follows: $\Delta STP = -0.183\ DEPTH + 0.00512\ DEPTH^2 - 0.0000207\ DEPTH^3$. Since the minimum observed DEPTH = 15 cm, all ΔSTP values were adjusted by subtracting the value for 15 cm from those computed for other depths in the profile. Thus, all ΔSTP values were relative to the value of 0 at DEPTH = 15 cm. For the quadratic functions of the other variables to be discussed later, a similar adjustment was made by setting ΔSTP = 0 at the minimum observed value of the variable, if it was greater than 0.

As shown in Figure 6, ΔSTP in MODEL C-23 had a minimum value at 20 cm (8 in.) and then increased to a maximum value at 145 cm (57 in.), which was greater than the deepest horizon included in the data. The change in STP with depth in MODEL C-23, which has no interactions between variables, is the change at constant or average values of all other variables.

The highly significant $DEPTH^3$ variate in MODEL C-23 was deleted in MODEL C-24 to determine how much this variate affected the estimated STP distribution with depth. The ΔSTP from the quadratic function in MODEL C-24 was: $\Delta STP = 0.0937\ DEPTH + 0.000688\ DEPTH^2$. This shows that STP increased at an increasing rate with depth in the profile, as shown in Figure 6. Because the STP distributions among soils varied from the decreasing pattern to slight sigmoid to marked sigmoid distributions, the average STP distribution with depth in this model reflects mostly

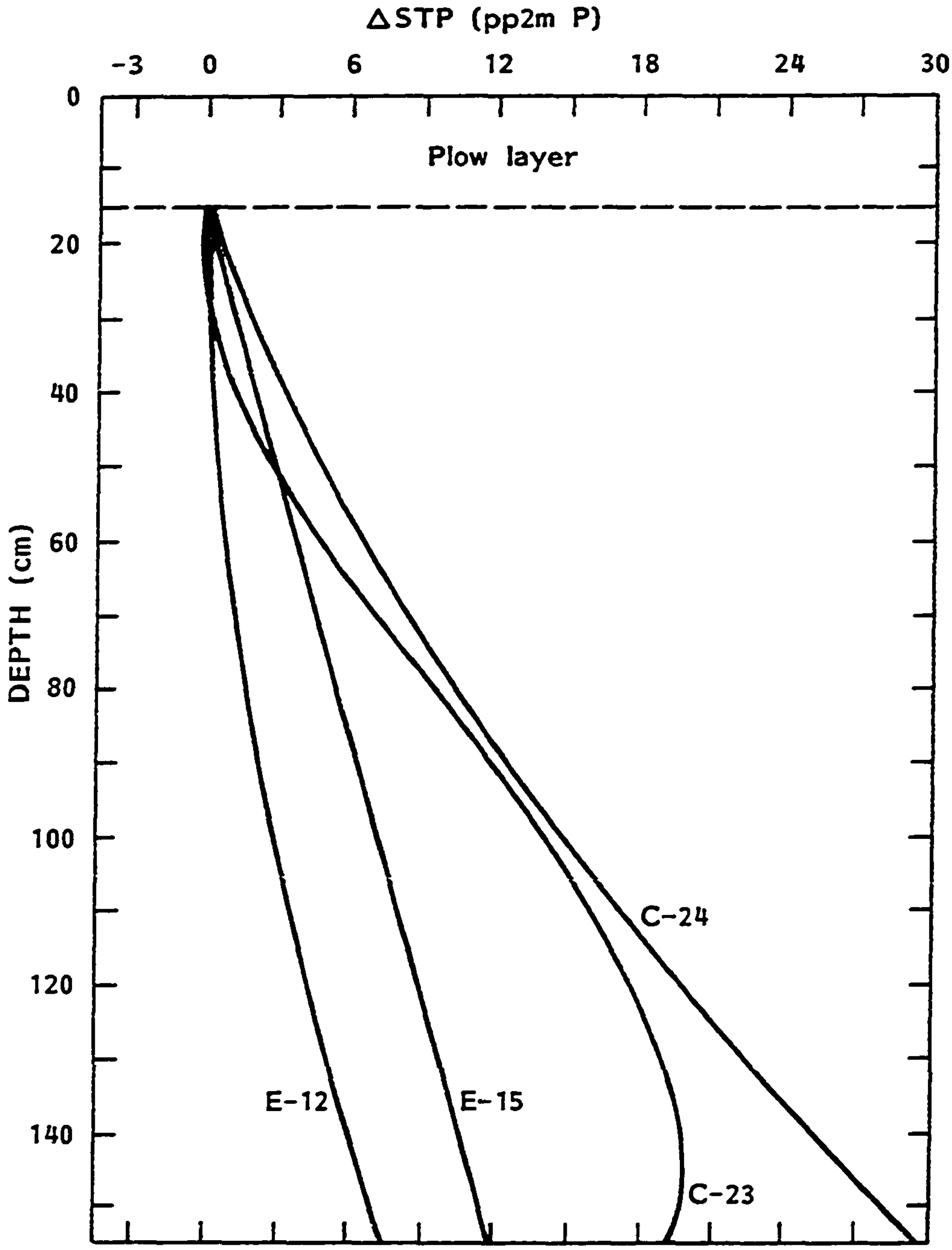

Figure 6. Change in STP (ΔSTP) with depth in MODELS C-23, C-24, E-12, and E-15

the frequency of the different distribution patterns in the data.

<u>GHP</u> The quadratic effect of GHP (coded genetic horizon) on STP in MODEL C-17 is $\Delta STP = -0.0189\ GHP + 0.001223\ GHP^2$. The dSTP/dGHP = −0.0189 + 0.002446 GHP; STPMIN occurred at GHP = 8. The STP then increased as coded GHP increased, as shown in Figure 7A.

In MODEL A-8 (Table 10), GHP had a linear effect on STP (Figure 7A); the ΔSTP from GHP = 0 to GHP = 80 was 8.2 pp2m P. The effect of GHP on STP in MODEL A-8 may have been distorted somewhat because of the presence of the DCAL variable with which it was correlated ($r = -0.53$).

<u>PH</u> The PH variable had a similar curvilinear effect on STP in both MODELS C-23 and D-22 (Tables 13 and 14). In MODEL C-23, the STP increased about 3 pp2m P as decoded PH increased from pH 4.5 to 5.7 (where STPMAX occurred); from pH 5.7 to pH 8.2, STP decreased about 13 pp2m P (Figure 7B). The average effect of PH from all horizons on STP in this study was similar to the average effect found in the previous study (Salih, 1979). In the 30-51 cm (12-20 in.) layer, PH had a curvilinear effect on STP; in the 76-107 cm (30-42 in.) layer, PH had a negative, linear effect.

<u>STK</u> The STK variable had a linear effect on STP in both MODELS C-23 and D-22 (Table 13). The difference between the STK coefficients in these two models may be due to a higher correlation between STK and RANGE ($r = 0.45$) than between STK and PPT ($r < 0.40$). In MODEL C-23, STP increased 0.019 pp2m P as STK increased one pp2m K. This effect was similar to that in the previous study (Salih, 1979). The relationship between STP and STK probably is only an association, not a

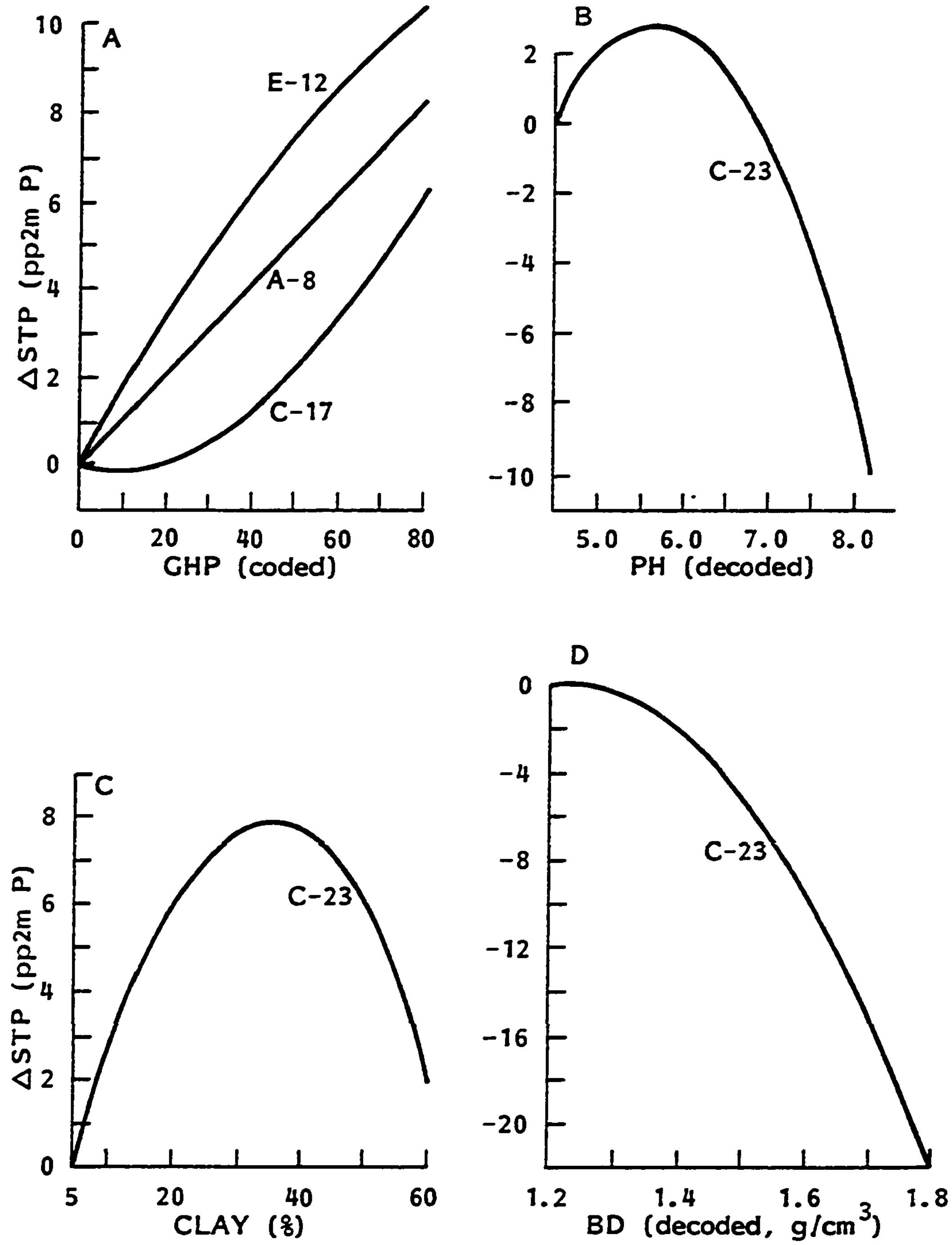

Figure 7. Change in STP (ΔSTP) with (A) coded genetic horizon (GHP), (B) decoded soil pH (PH), (C) percent clay (CLAY), and (D) decoded bulk density (BD)

cause and an effect relationship.

CLAY The percentage of clay (CLAY) had a similar curvilinear effect on STP on both MODELS C-23 and D-22 (Tables 13 and 14). In MODEL C-23, the STP increased about 8 pp2m P as CLAY increased from 5% to 35% (where the maximum STP occurred) and then STP decreased about 6 pp2m P as clay percentage increased from 35% to 60% (Figure 7C). The trend and magnitude of the CLAY effect on STP was similar to the previous study (Salih, 1979) in which STPMAX occurred at 27% and 31% clay in the two fixed layers of 30-51 and 76-107 cm in the profile, respectively.

BD The BD variable (bulk density) had a similar curvilinear effect in both MODELS C-23 and D-22 (Tables 13 and 14). In MODEL C-23, STPMAX occurred at decoded BD = 1.22; as BD increased from 1.22 to 1.80, STP decreased about 22 pp2m P (Figure 7D). The BD variable also had similar effects on STP in MODELS A-8 and B-9 (Tables 10 and 11).

Because BD was highly correlated with TILL parent material ($r = 0.72$) and SAND ($r = 0.70$), it accounts for much of the effect of the TILL parent material (not included in this model), and of the ALLUV-T parent material (deleted because of nonsignificance), many of which are sandy in the lower profile. In the bulk density range of 1.2 to 1.4 g/cm^3 which included most of the deep loess soils, BD had a slight effect on STP (up to 2 pp2m P).

The BD effect on STP had a similar trend in the previous study by Salih (1979), except that STPMAX was associated with higher BD values.

He found that the BD values associated with STPMAX in the fixed profile layers of 30-51 and 76-107 cm were 1.30 and 1.36 g/cm^3, respectively.

<u>Parent materials</u> All parent material variables retained in MODELS C-23 and D-22 had similar linear effects on STP (Table 13). Only the effects of PEDISED and EOLIAN on STP differed some from those in MODELS A-8 and B-9 (Table 10). The regression coefficient for PEDISED in MODEL C-23 of -1.57 indicated that the average STP of PEDISED parent material was 1.6 pp2m less than the average STP of all other soils. The COLLUV-L parent material had 6.6 pp2m less STP, ALLUV-L had 6.4 pp2m higher STP, and EOLIAN sand had 9.1 less STP than the average STP of all other parent materials. These parent material effects on STP were similar to those reported previously (Salih, 1979).

<u>THAHOR</u> The thickness of A horizon (THAHOR) variable had identical curvilinear effects on STP in both MODELS C-23 and D-22 (Tables 13 and 14). The minimum STP level occurred at THAHOR = 28 cm (11 in.) and then STP increased as the THAHOR increased (Figure 8A). The effects of THAHOR up to 60 cm (24 in.) on STP were slight; all profiles with THAHOR >60 cm were colluvium, alluvium, and lacustrine parent materials. In MODELS A-8 and B-9, THAHOR had a linear, positive effect on STP. The effect of THAHOR on STP in MODELS C-23 and D-22 was similar to that reported previously (Salih, 1979).

<u>DRAIN</u> The DRAIN variable (coded drainage class) had a similar curvilinear effect on STP in both final reduced prediction models, MODELS C-23 and D-22 (Tables 13 and 14), and also in MODELS A-8 and B-9 (Tables 10 and 11). As shown in Figure 8B for MODEL C-23, STP decreased

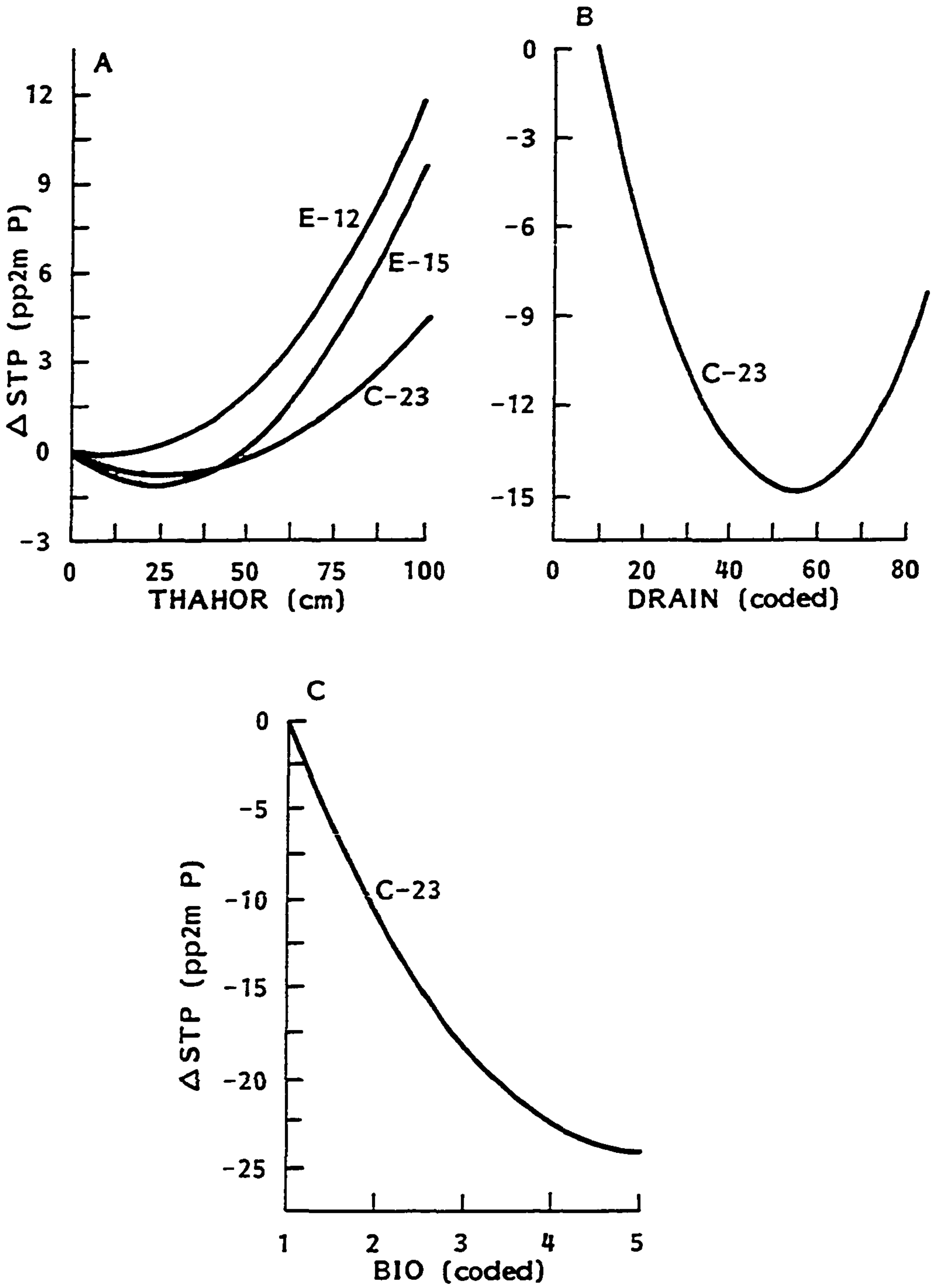

Figure 8. Change in STP (ΔSTP) with (A) thickness of A horizon (THAHOR), (B) coded drainage class (DRAIN), and (C) coded biosequence (BIO)

as DRAIN increased from 10 (excessive) to a minimum at DRAIN = 55 (between somewhat poor and somewhat poor to poor) and then increased as DRAIN became poorer. A similar effect of DRAIN on STP in both the 30-51 cm and 76-107 cm layers was reported previously (Salih, 1979).

The increase in estimated STP at DRAIN > 55 probably is because several of the poorly to very poorly drained soils derived from alluvium, Colo, Zook, and Wabash, had higher STP than many of the better drained soils. Addition of interaction variates with DRAIN in the interaction models may explain this apparent deviant behavior of poor drainage on STP.

<u>BIO</u> The biosequence (BIO) variable had a large, similar curvilinear effect on STP in both MODELS C-23 and D-22 (Tables 13 and 14). STP decreased from BIO = 1 (forest) to BIO = 5 (prairie) which was associated with minimum STP (Figure 8C). The BIO variable had a dominant and stable effect on STP in all models of this study and of the previous study (Salih, 1979).

<u>DPHMIN</u> The DPHMIN variable (depth to midpoint of the minimum pH layer in the profile) had a similar linear effect on STP in both MODELS C-23 and D-22 (Table 13). The STP increased 0.14 pp2m as the DPHMIN increased one cm. Also, DPHMIN had similar regression coefficients in previous MODELS A-8 and B-9 (Table 10).

<u>PPT</u> The PPT variable (mean annual precipitation) had a curvilinear effect on STP in MODEL C-23 (Tables 13 and 14). A similar effect of PPT on STP occurred in MODEL A-8 (Tables 10 and 11). In MODEL C-23, STP increased 9.6 pp2m P as decoded PPT increased from 63

cm (25 in.) to 85 cm (33.5 in.) which associated with STPMAX, and then decreased 0.3 pp2m P as decoded PPT increased to 89 cm (35 in.), as shown in Figure 9A. Most of the increase in STP (8 pp2m P) occurred from PPT = 63 cm (25 in.) to 76 cm (30 in.); this area of the state is north and west of a line from central Harrison County to the northwest corner of Hamilton County and north to the Iowa border (Figure 2). The effect of PPT on STP is related to increased weathering and decreased pH in the subsoil as PPT increased.

TEMP The TEMP variable (mean annual temperature) had a similar curvilinear effect on STP in MODELS C-23 (Tables 13 and 14) and A-8 (Tables 10 and 11). As shown in Figure 9B for MODEL C-23, STP increased 1.5 pp2m P as TEMP increased from decoded 7 °C to 8.4 °C (47 °F), associated with STPMAX. The 47 °F isoline occurs in northcentral Iowa (Figure 3). From decoded 8.4 °C to 11 °C (52 °F), STP decreased 5.6 pp2m P. The effect of TEMP on STP is related to the speed of the chemical reactions in the soil and degree of weathering. The TEMP variable had less effect on STP than the PPT variable.

TWP The TWP variable (S-N direction) had a curvilinear effect on STP in MODEL D-22 (Tables 13 and 14). The STP increased about 2.5 pp2m from TWP 65 at the southern edge of Iowa to TWP 85 in central Iowa, where STPMAX occurred (Figure 9C). From TWP 85 to TWP 100, STP decreased 1.5 pp2m P. The effect of TWP on STP was similar to that of TEMP with which it was highly correlated (r = -0.96). The trend of the TWP effect on STP also was similar to that in the previous study of Salih (1979).

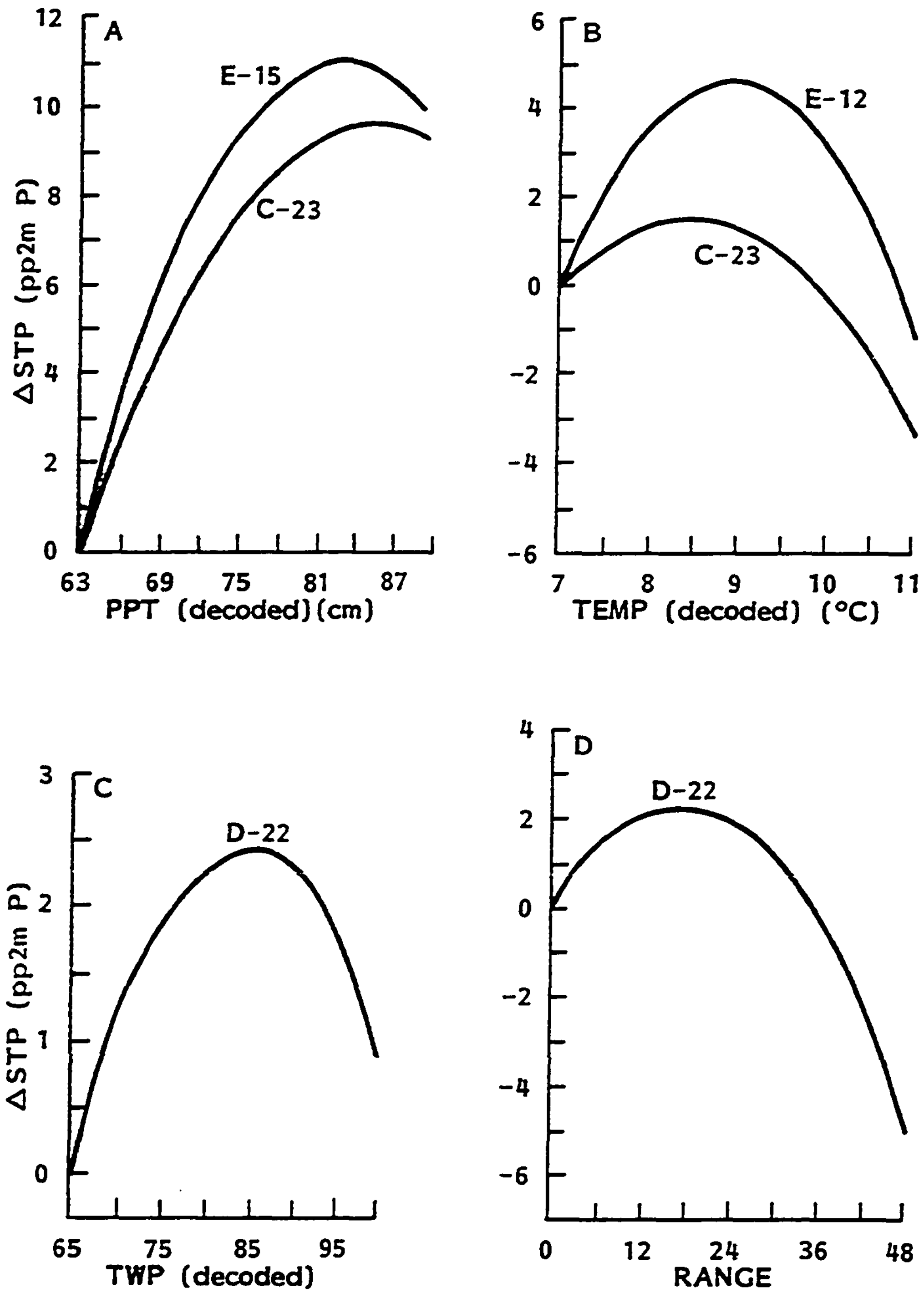

Figure 9. Change in STP (ΔSTP) with (A) decoded precipitation (PPT), (B) decoded temperature (TEMP), (C) decoded township number (TWP), and (D) range number (RANGE)

RANGE In MODEL D-22 (Tables 13 and 14), the RANGE variable (E-W direction) had an effect on STP similar to its effect in MODEL B-9 (Tables 10 and 11). From RANGE = 0 (R1E) to RANGE = 17W (associated with STPMAX), STP increased 2.2 pp2m P (Figure 9D). From RANGE = 17 to RANGE = 48, STP decreased about 7 pp2m P. These results are similar to the previous study (Salih, 1979). The effect of RANGE on STP was similar to that of PPT with which it was highly correlated (r = -0.85). The RANGE variable had more effect on STP than the TWP variable (Figures 9C and 9D).

Multiple regressions of STP on all variables except horizon variables, MODELS E and F series

The first and major objective of the MODELS E and F series of regression models was to determine the relative importance of the horizon variables for estimating STP. These variables (PH, STK, SAND, SILT, CLAY, OC, and BD) were deleted in the MODELS E and F series. The determination or estimation of these variables involves considerable cost and time because all must be analyzed or estimated for each horizon of the profile. If subsoil P can be estimated with almost the same precision (same R^2) from all other variables except the horizon group, considerable cost and time can be saved for subsoil P estimations in future studies.

Salih (1979) studied the effects of deleting the soil horizon variables on predicting STP in two fixed profile layers of 30-51 and 76-107 cm deep in a series of regression models. He found that their deletion reduced the R^2-values very slightly for predicting STP1 in the

30-51 cm layer but about 0.03 to 0.04 for predicting STP2 in the 76-107 cm layer. He concluded that STP could be estimated with good precision if the horizon variables were not included.

The second objective was to compare again the effects of climatic variables and location variables for estimating STP. These variables were compared in alternate parallel models in the MODELS E and F series in the absence of horizon variables.

The third objective was to determine the relative effects of the GHP variable on STP in the absence of horizon variables. Additional regression models were computed in which the GHP variable was deleted in both the MODELS E and F series.

Model selection The initial regression of STP (MODEL E-1) on linear functions of the parent material variables, cubic function of the depth variable, and quadratic functions of all other variables except the location variables (TWP and RANGE) included 49 variates and had an R^2-value of 0.631 (Table 15). In MODEL E-2 the horizon variables of PH, STK, SAND, CLAY, OC, and BD and the nonsignificant SLCONF variable were deleted from MODEL E-1. Deletion of these variables reduced the R^2 to 0.588. MODEL E-2 then was used as the base model for further model selections.

In MODELS E-3 to E-10 the correlated variables of PHMIN, DCAL, DCMAX, DRAIN, THAHOR, EROS, and SLOPE were tested in alternate models. In MODEL E-11, the DCAL, CMAX, and EROS variables were deleted because they gave lower R^2 than their correlated variables of PHMIN, DRAIN, and THAHOR, respectively. The nonsignificant $DEPTH^3$ variate was deleted in

Table 15. Model selection steps, MODELS E and F series

Model no.	No. of X variates	Model selection steps	R^2
E- 1	49	Same as MODEL A-3, PPT and TEMP variables included but TWP and RANGE variables deleted	.6306
2	35	From MODEL E-1, deleted horizon variables of PH, STK, SAND, CLAY, OC, and BD and nonsignificant SLCONF profile variable	.5875
3 to 10	29 to 33	Tested correlated variables of PHMIN, DCAL, CMAX, DRAIN, THAHOR, EROS, and SLOPE in alternate models by deleting variables from MODEL E-2	.5745 to .5869
11	29	Deleted DCAL, CMAX, and EROS variables from MODEL E-2 because correlated PHMIN, DRAIN, and THAHOR variables, respectively, gave higher R^2 in alternate models	.5779
12	28	Deleted ns $DEPTH^3$ from MODEL E-11; final model with GHP variable	.5778
13	27	Deleted GHP and GHP^2 variates from MODEL E-11	.5465
15	25	Deleted ns $DEPTH^3$ and $DEPTH^2$ variates stepwise from MODEL E-13; final model without GHP variable	.5463
F- 1	49	Same as MODEL B-3, TWP and RANGE included but PPT and TEMP deleted	.6257
2	35	From MODEL F-1, deleted horizon variables and ns SLCONF profile variable	.5807
12	28	Deleted same variates as were deleted from MODELS E-2 to E-12; final model with GHP variable	.5709
15	25	Deleted GHP, GHP^2, and $DEPTH^2$ variates from MODEL F-12; final model without GHP variable	.5373

MODEL E-12 which was the final model with the GHP variable present.

The GHP variable was next deleted from MODEL E-11 to determine the effect of GHP on the prediction of STP (Table 15). For the final model without the GHP variable (MODEL E-15) the nonsignificant variates of $DEPTH^3$ and $DEPTH^2$ were deleted stepwise from MODEL E-13.

The model selection for the MODEL F series (with the location variables substituted for the climatic variables) involved identical steps and variates; R^2-values were slightly less than those in the corresponding MODEL E series (Table 15).

The R^2-value of the final MODEL C-17 was 0.613 (Table 12); deletion of the horizon variables in final MODEL E-12 reduced the R^2 to 0.578 (Table 15). This was similar to the reduction reported by Salih (1979).

The deletion of the GHP variable caused a loss in R^2 of 0.032 in the MODEL E series and of 0.009 in the C series (Tables 12 and 15). The deletion of the PH variable in the MODEL E series thus increased the importance of the GHP variable.

Effect of selected variables on STP The regression statistics for the variates retained in the final MODELS E-12 (with the GHP variable) and E-15 (without the GHP variable) are given in Table 16. The regression statistics for the MODEL F series (with location variables) are not shown and will not be discussed because they were very similar to those of the MODEL E series in Table 16. The values of the variables associated with STPMIN or STPMAX for those having quadratic functions are given in Table 17 for MODELS E-12 and E-15.

All of the variables had similar effects on STP in both final MODELS E-12 and E-15 except the PHMIN variable and the DEPTH variable which had a quadratic effect in MODEL E-12 and a linear effect in MODEL

Table 16. Regression statistics of STP on all variables except horizon and location variables, MODELS E-12 and E-15

X_i	Variable	Regression coefficients (b_i) MODEL E-12 Linear	MODEL E-12 Squared	MODEL E-15 Linear	MODEL E-15 Squared
1,34	DEPTH	-0.0105	0.000375*	0.0863**	--
2,36	GHP	0.186**	-0.000685++	--	--
12	PEDISED	-6.57**	--	-6.91**	--
13	TILL	-11.25**	--	-12.53**	--
14	COLLUV-L	-8.10**	--	-8.07**	--
15	ALLUV-L	4.45**	--	4.47**	--
16	ALLUV-T	-5.99**	--	-5.31**	--
17	EOLIAN	-18.22**	--	-18.73**	--
20,48	SLOPE	0.403**	-0.0281**	0.570**	-0.0369**
23,51	THAHOR	-0.0362	0.00154**	-0.0878*	0.00183**
24,52	DRAIN	-0.652**	0.00588**	-0.688**	0.00635**
25,53	BIO	-15.18**	1.531**	-14.47**	1.417**
27,55	PHMIN	0.937	-0.512*	3.586**	-1.576**
28,56	DPHMIN	0.280**	-0.00134*	0.330**	-0.00183**
30,58	DCMAX	0.108**	-0.000593*	0.0961**	-0.000565*
31,59	PPT	0.949**	-0.0248**	1.136**	-0.0291**
32,60	TEMP	4.86**	-1.283**	4.75**	-1.265**
Intercept		40.2**		39.3**	
R^2		0.578**		0.546**	

E-15 (Table 16).

Deletion of the horizon variables changed the mix of the variables retained in the MODEL E series compared to those in the MODEL C series. The TILL and PHMIN variables included in the MODEL E series had been deleted in the MODEL C series because the highly correlated BD and PH variables gave higher R^2 in alternate models. The ALLUV-T, SLOPE, and DCMAX variables had significant effects in the MODEL E series but had

Table 17. Computed values of the variables associated with maximum or minimum STP, MODELS E-12 and E-15

Variable	MODEL E-12		MODEL E-15	
	STPMAX or STPMIN	Value	STPMAX or STPMIN	Value
DEPTH	MIN	14 cm (6 in.)	--	--
GHP	MAX	136; decoded, >80 = C horizon	--	--
SLOPE	MAX	7.2%	MAX	7.7%
THAHOR	MIN	11.8 cm (4.6 in.)	MIN	24 cm (9.4 in.)
DRAIN	MIN	55; somewhat poor	MIN	54; somewhat poor
BIO	MIN	5.0; prairie	MIN	5.1; prairie
PHMIN	MAX	0.9; decoded = pH 5.4	MAX	1.1; decoded = pH 5.6
DPHMIN	MAX	104 cm (41 in.)	MAX	90 cm (36 in.)
DCMAX	MAX	91 cm (36 in.)	MAX	85 cm (33 in.)
PPT	MAX	19.1; decoded 82.1 cm (32.3 in.)	MAX	19.5 cm; decoded = 82.5 cm (32.5 in.)
TEMP	MAX	1.9; decoded = 8.9 °C (48 °F)	MAX	1.9; decoded = 8.9 °C (48 °F)

been deleted because of nonsignificance in the MODEL C series; these changes show some intercorrelation between these variables and some of the horizon variables.

Most of the variables that occurred in the final models of both the MODEL C and E series had somewhat different magnitude effects on STP. The DRAIN and BIO variables had similar effects in both series of models and will not be discussed. The effects of the others on STP will be discussed briefly in the following paragraphs.

<u>DEPTH</u> The DEPTH variable had a curvilinear effect on STP in MODEL E-12 (with the GHP variable) and a linear effect in MODEL E-15 (without the GHP variable), as shown in Table 16. This difference is probably due to the correlation between DEPTH and GHP ($r = 0.47$). These effects of the DEPTH variable on STP are shown in Figure 6. All ΔSTP values are relative to the value of 0 at DEPTH = 15 cm, as was done in the previous section. In MODEL E-12, the STPMIN occurred at DEPTH = 14 cm (Table 17); STP then increased with DEPTH in a slight curvilinear manner. In MODEL E-15 without the GHP variable, the increase in STP with DEPTH was larger than in MODEL E-12 (Figure 6). The ΔSTP with DEPTH in MODELS E-12 and E-15, however, were considerably less in the lower profile than in MODELS C-23 and C-24.

<u>GHP</u> The GHP variable had a slight curvilinear effect on STP in MODEL E-12 (Figure 7A). The STP increased about 7 pp2m P as the coded GHP increased from 20 (A_3 - B_1 horizon) to 80 (C horizon). The calcareous C horizon (GHP = 0) had about 10 pp2m less P than the leached C horizon (GHP = 80). The difference in the effects of GHP on STP in MODELS C-17 and E-12 is probably due to the presence of the PH variable in the first model and its absence in the second one. The unstable effects of GHP cn STP in the three models (Figure 7A) show the presence of intercorrelation among the variables.

<u>Parent materials</u> In the absence of the horizon variables, the effects of PEDISED and EOLIAN on STP were greater in the MODEL E

than MODEL C series (Tables 13 and 16). The ALLUV-T variable had a significant, negative effect on STP in MODELS E-12 and E-15 but none in MODEL C-23. The TILL variable had a large negative effect on STP in both MODELS E-12 and E-15. All of these parent material variables were accounting for the large effect of BD on STP in MODEL C-23 as shown in Figure 7D. The effects of the silty, low bulk density COLLUV-L and ALLUV-L parent materials on STP were only slightly different in the MODEL C and E series.

<u>SLOPE</u> In MODELS E-12 (with GHP) and E-15 (without GHP), SLOPE had a similar curvilinear effect on STP but differed some in magnitude (Figure 10A). The slopes associated with STPMAX in MODELS E-12 and E-15 were 7.2% and 7.7%, respectively. These were similar to those reported by Salih (1979). The effect of SLOPE may be distorted because of its high correlations with THAHOR and DRAIN (Table 6).

<u>THAHOR</u> The THAHOR had similar curvilinear effects on STP in both MODELS E-12 (with GHP) and E-15 (without GHP) although their magnitudes differed some (Figure 8A). The STPMIN occurred at THAHOR = 12 cm (4.6 in.) and 24 cm (9.4 in.) in MODELS E-12 and E-15, respectively (Tables 16 and 17). The THAHOR variable had larger effects on STP in the MODEL E series than in MODEL C-23 probably due to the correlation between THAHOR and SLOPE ($r = -0.57$).

<u>PHMIN</u> The PHMIN variable had different curvilinear effects on STP in MODELS E-12 and E-15 (Figure 10B) although the PHMIN levels at STPMAX were similar (Table 17). In MODEL E-12 (with GHP), the effect of PHMIN on STP was slight. In MODEL E-15 (without GHP), PHMIN had a

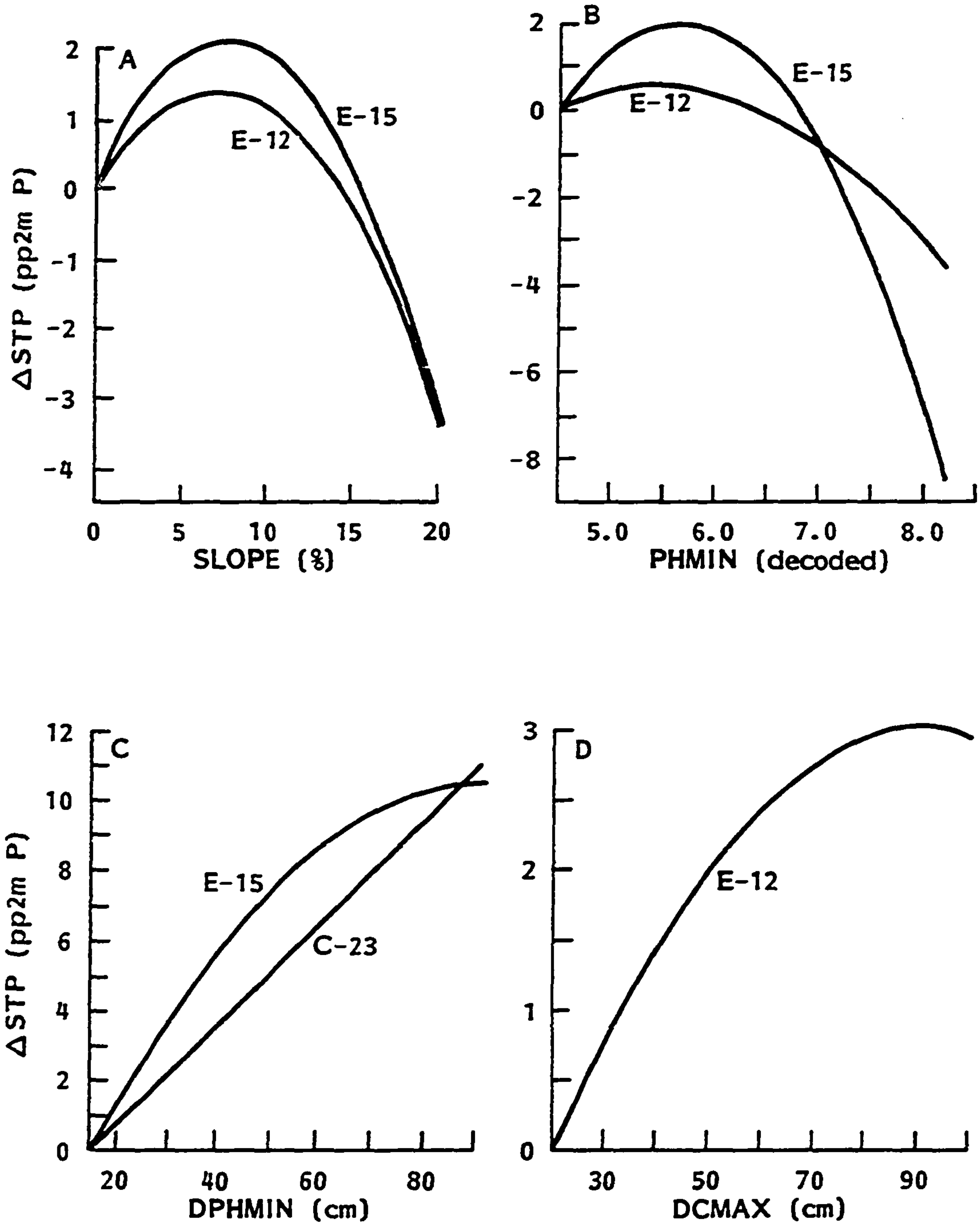

Figure 10. Change in STP (ΔSTP) with (A) SLOPE, (B) decoded minimum pH (PHMIN), (C) depth to minimum pH (DPHMIN), and (D) depth to maximum clay (DCMAX)

greater effect on STP, particularly above pH 6.5. The effect of PHMIN on STP in MODEL E-15 was similar to the effect of the PH variable in MODEL C-23 shown in Figure 7B; neither model included the GHP variable.

DPHMIN The DPHMIN variable (depth to the midpoint of minimum pH layer) had almost identical curvilinear effects on STP in both MODELS E-12 and E-15 (Tables 16 and 17). The effect of DPHMIN on STP in MODEL E-15 is shown in Figure 10C; STP increased about 10.3 pp2m P as DPHMIN in the profile increased from 15 cm to 90 cm (36 in.), where STPMAX occurred. In MODEL C-23 which included the horizon variables, DPHMIN had a positive linear effect on STP (Table 13 and Figure 10C).

DCMAX The DCMAX variable (depth to the midpoint of the maximum clay layer) had almost identical curvilinear effects on STP in both MODELS E-12 and E-15. In MODEL E-12, STP increased about 3 pp2m P as DCMAX increased from 20 cm (8 in.) to 91 cm (36 in.), where the STPMAX occurred (Figure 10D).

PPT In both MODELS E-12 (with GHP variable) and E-15 (without GHP variable), PPT (mean annual precipitation) had similar curvilinear effects on STP. The effect of PPT on STP in MODEL E-15 is shown in Figure 9A; its effect was similar to that in MODEL C-23.

TEMP The TEMP variable (mean annual temperature) had an identical curvilinear effect on STP in both MODELS E-12 and E-15 (Tables 16 and 17). The effect of TEMP on STP in MODEL E-12 is shown in Figure 9B. Deletion of the horizon variables in the MODEL E series increased the effect of TEMP on STP as shown by its effect on STP in MODEL C-23 (Figure 9B).

Summary of MODELS A to F series

Multiple regressions of STP were initially computed in the MODELS A to F series on the quadratic functions of all variables except for linear functions of the parent material variables (which were dummy or linear variables) and the cubic function of the DEPTH variable. The cubic function of DEPTH was included to explain the sigmoid distribution of STP in many Iowa soils.

Different regressions were selected for varying degrees of correlation between the variables, as follows: (1) high correlations disregarded (MODELS A and B series); and (2) no variables included which were correlated greater than ±0.60 (MODELS C and D series).

To compare the relative effects of climatic variables (PPT and TEMP) and location variables (TWP and RANGE) on STP, alternate models were computed. The climatic variables were included in the MODELS A, C, and E series; location variables were included in the MODELS B, D, and F series.

The horizon variables were deleted in MODELS E and F to test how well STP could be predicted without including the horizon variables. Also, additional models were computed in the MODELS C to F series to determine the importance of the GHP variable for predicting STP.

The final complete prediction MODEL A-8 (with climatic variables) and MODEL B-9 (with location variables), in which the high correlations were disregarded, had R^2-values of 0.630 and 0.625, respectively. The final MODELS C-17 and D-17, in which no variables were included that were correlated greater than ±0.60, had R^2-values of 0.613 and 0.608, respectively. Thus, deletion of highly correlated variables reduced the R^2 by 0.017. Deletion of the GHP variable (intercorrelated with several other variables) further reduced the R^2-values of the final MODELS C-23 and D-22 to 0.605 and 0.601, respectively.

The relationships between the variables and STP under conditions of minimum distortion of the regression coefficients due to intercorrelations among variables were of more interest in this study than maximum precision in predicting STP (highest R^2). Therefore, the significant variates in final MODEL C-23 were included in the initial interaction models.

In all models with climatic variables (MODELS A, C, and E), the R^2-values were slightly higher than those with the location variables (MODELS B, D, and F). This indicated that the climatic variables of PPT and TEMP were slightly better for predicting STP than the location variables of TWP and RANGE. Only the climatic variables were included in the subsequent interaction models.

Deletion of the horizon variables in the final MODEL E-12 reduced the R^2 to 0.578, about 0.035 less than the R^2 of the comparable MODEL C-17. This agreed with the previous study by Salih (1979). Deletion of the GHP variable in final MODEL E-15 reduced the R^2 to 0.546, a decrease of 0.032 from that of MODEL E-12. The GHP variable had a slight effect on STP in the MODEL C series and was deleted from the subsequent interaction models. However, it had much more effect on STP in the absence of the horizon variables (primarily the PH variable) and was included in one of the final interaction models.

The following variables had significant effects on STP in MODEL C-23: linear functions of STK, PEDISED, COLLUV-L, ALLUV-L, EOLIAN, and DPHMIN; quadratic functions of PH, CLAY, BD, THAHOR, DRAIN, BIO, PPT, and TEMP; and the cubic function of DEPTH. In final MODEL E-12 (horizon variables deleted), the following had significant effects on STP: linear functions of all parent material variables and quadratic functions of DEPTH, GHP, SLOPE, THAHOR, DRAIN, BIO, PHMIN, DPHMIN, DCMAX, PPT, and TEMP. The effect of each variable on STP in the final models in the different series had the same trend although the magnitudes of several varied because of intercorrelations.

Multiple Regressions of STP on Selected Variables and Interactions with DEPTH, MODELS G and H Series

Because the main objective of the present study was to develop regression equations to predict the subsoil P distributions in soil profiles for a wide range of soil, location, and climatic variables, the depth variable had to be included. The sigmoid P distributions in many profiles also indicated that a cubic function of the depth variable should be included. The wide variation in subsoil P levels with depth indicated that many linear*linear interactions between depth and other variables should be tested. The variation in the minimum and maximum subsoil P levels and depths to the minimum and maximum levels in the profiles with sigmoid distributions of subsoil P also indicated that depth was involved in complex interactions between the quadratic and even the cubic functions of depth and other variables.

For these models and all subsequent ones, the climatic variables were included and the location variables were deleted. The GHP variable was not included in these models. For the MODEL G series, the significant variates in MODEL C-23 were included as the base set plus the ALLUV-T, SLOPE, and DCMAX variables which were added for further testing. For the MODEL H series (horizon variables deleted), the significant variates in final MODEL E-15 were included as the base set and only the $DEPTH^2$ and $DEPTH^3$ variates were added.

To the base set of variates included in the MODELS G and H series, all $DEPTH*X_i$ (linear*linear), all $DEPTH^2*X_i$ (quadratic*linear) and all $DEPTH^3*X_i$ (cubic*linear) interactions except $DEPTH^3$*STK, $DEPTH^3$*PEDISED, and $DEPTH^3$*EOLIAN were added and tested for significance. Because the Helarctos II regression program is limited to 100 variates, only the large number of interactions involving DEPTH could be tested in the presence of linear, quadratic, and cubic functions of the selected variables.

For these and all subsequent models, the unit of the DEPTH variable was transformed from cm to meters. This was done to avoid very small regression coefficients resulting from large values of $DEPTH^3$ if DEPTH were in cm units (range of 15-137 cm).

Model selection

All variates listed in Table 18 were included in the MODEL G series except the TILL and PHMIN variables and all of their associated squared and interaction variates. These two variables had been deleted in the MODEL C series because of their high correlations with BD and PH, respectively. The R^2-values of the initial MODEL G-1 with 79 variates

Table 18. Variates included in the multiple regressions of STP on linear, quadratic, and cubic functions of selected variables and on interactions of DEPTH, $DEPTH^2$, and $DEPTH^3$ with all variables, MODELS G and H series

X_i[a]	Variate	X_i	Variate	X_i	Variate
1	DEPTHCM	37	$PHMIN^2$	69	$DEPTH^2$*COLLUV-L
3	PH	38	$DPHMIN^2$	70	*ALLUV-L
4	STP[b]	39	$DCMAX^2$	71	*ALLUV-T
5	STK	40	PPT^2	72	*EOLIAN
6	CLAY	41	$TEMP^2$	74	*SLOPE
7	BD			75	*THAHOR
		43	DEPTH*PH		
8	PEDISED	44	*STK	76	*DRAIN
9	TILL	45	*CLAY	77	*BIO
10	COLLUV-L	46	*BD	78	*PHMIN
11	ALLUV-L	47	*PEDISED	79	*DPHMIN
12	ALLUV-T	48	*TILL	80	*DCMAX
13	EOLIAN			81	*PPT
		49	*COLLUV-L	82	*TEMP
14	SLOPE	50	*ALLUV-L		
15	THAHOR	51	*ALLUV-T	84	$DEPTH^3$*PH
16	DRAIN	52	*EOLIAN	85	*CLAY
17	BIO	53	*SLOPE	86	*BD
18	PHMIN	54	*THAHOR	87	*TILL
19	DPHMIN			88	*COLLUV-L
20	DCMAX	55	*DRAIN		
21	PPT	56	*BIO	89	*ALLUV-L
22	TEMP	57	*PHMIN	90	*ALLUV-T
		58	*DPHMIN	91	*SLOPE
23[c]	DEPTH	59	*DCMAX	92	*THAHOR
25	$DEPTH^2$	60	*PPT	93	*DRAIN
26	$DEPTH^3$	61	*TEMP	94	*BIO
30	PH^2				
31	$CLAY^2$	63	$DEPTH^2$*PH	95	*PHMIN
32	BD^2	64	*STK	96	*DPHMIN
33	$SLOPE^2$	65	*CLAY	97	*DCMAX
34	$THAHOR^2$	66	*BD	98	*PPT
35	$DRAIN^2$	67	*PEDISED	99	*TEMP
36	BIO^2	68	*TILL		

[a]The X_i variates not listed were not used in these regressions.

[b]STP was the dependent (Y) variable.

[c]DEPTH (X23) was DEPTHCM (X1) transformed to meters (X1 in cm*0.01); this coded DEPTH variate was used in all transformations (squared, cubic, and interaction variates) in this and subsequent analyses.

and the final MODEL G-10 with 57 variates were 0.675 and 0.673, respectively (Table 19). Addition of the ALLUV-T, SLOPE, and DCMAX variables and all of the significant interactions with DEPTH increased the R^2 of MODEL G-10 to 0.673 from the R^2 of 0.605 for MODEL C-23.

The method of selecting the significant DEPTH interactions involved deletion of the nonsignificant $DEPTH^3*X_i$ variates first, then deletion of nonsignificant $DEPTH^2*X_i$ interactions if the $DEPTH^3*X_i$ interactions had been deleted in a previous step, and then deletion of the nonsignificant $DEPTH*X_i$ interactions if the $DEPTH^2*X_i$ had been deleted previously. Thus, a lower-order DEPTH interaction was retained regardless of its significance level if its higher-order interaction with a variable was significant.

Table 19. Model selection steps, MODELS G and H series

Model no.	No. of X variates	Model selection steps	R^2
G- 1	79	Initial model; all variates listed in Table 18 except DEPTHCM (X1), TILL and its associated interactions, and PHMIN, $PHMIN^2$, and associated interactions	.6753
G-10	57	Final model; deleted nonsignificant interaction variates and $DCMAX^2$ stepwise from MODEL G-1	.6726
H- 1	70	Initial model; all variates listed in Table 18 except DEPTHCM and the horizon variables of PH, STK, CLAY, and BD (all linear, squared, and interaction variates)	.6427
H- 8	48	Final model; deleted nonsignificant interaction variates stepwise from MODEL H-1	.6395

All variates listed in Table 18 were included in the MODEL H series except the horizon variables of PH, STK, CLAY, and BD which included their linear and associated squared and interaction terms. The R^2 of the initial MODEL H-1 with 70 variates and final MODEL H-8 with 48 variates were 0.643 and 0.640, respectively (Table 19). Addition of $DEPTH^2$, $DEPTH^3$, and all of the significant DEPTH interactions increased the R^2 of MODEL H-8 to 0.640 from the R^2 of 0.546 in MODEL E-15.

Effects of DEPTH interactions on STP

The regression statistics for final MODELS G-10 and H-8 are given in Table 20. In MODEL G-10, 2 of 14 $DEPTH^3*X_i$ interactions tested, 9 of 17 $DEPTH^2*X_i$, and 16 of 17 $DEPTH*X_i$ interactions had significant effects on STP, with most significant at the 1% level. In MODEL H-8, 2 of 13 $DEPTH^3*X_i$, 4 of 15 $DEPTH^2*X_i$, and all 15 $DEPTH*X_i$ interactions tested were significant mostly at the 1% level.

Most of the regression coefficients of corresponding variates in MODELS G-10 and H-8 were similar. Only ones that varied were some of the linear variates that were not significant, some of the interactions between DEPTH and parent material variables, DCMAX because $DCMAX^2$ was deleted in MODEL G-10 and not in MODEL H-8, and DEPTH*PPT and DEPTH*TEMP because their associated $DEPTH^2$ interactions were deleted in MODEL H-8 but not in G-10.

The effects of different combinations of interactions between DEPTH and the other variables on STP will be illustrated using several selected variables. The effects of the other variables on STP in these models will not be discussed because their effects will be discussed in the

Table 20. Regression statistics of STP on selected variates in the final models on all variables, MODEL G-10, and on all except horizon variables, MODEL H-8

X_i	Variate[a]	Regression coefficients (b_i)	
		MODEL G-10	MODEL H-8
3	PH (2.2;0.4-3.8)	0.981	—
5	STK (49;10-370)	0.0185**	—
6	CLAY (29;3-61)	0.311*	—
7	BD (41;18-81)	1.028**	—
8	PEDISED (0.15;0-1)	1.90^{++}	1.07
9	TILL (0.19;0-1)	—	0.35
10	COLLUV-L (0.03;0-1)	1.59	0.25
11	ALLUV-L (0.08;0-1)	9.62**	10.22**
12	ALLUV-T (0.05;0-1)	4.66**	5.78**
13	EOLIAN (0.02;0-1)	3.88^{+}	-1.08
14	SLOPE (4.4;0-20)	0.0765	0.271
15	THAHOR (34;0-109)	-0.117**	-0.166**
16	DRAIN (44;10-85)	-0.718**	-0.584**
17	BIO (4.6;1-5)	-2.601^{+}	-3.080^{++}
18	PHMIN (1.7;0.4-3.6)	—	5.259**
19	DPHMIN (32;15-94)	0.415**	0.469**
20	DCMAX (52;18-122)	0.0379	0.0855*
21	PPT (17;0.2-26.2)	0.556**	0.883**
22	TEMP (2.0;0.2-3.8)	3.56**	2.932**
23	DEPTH (0.7;0.15-1.37)	261.1**	271.3**
25	$DEPTH^2$	-313.3**	-345.6**
26	$DEPTH^3$	116.9**	133.0**
30	PH^2	-0.881**	—
31	$CLAY^2$	-0.00877**	—
32	BD^2	-0.0149**	—
33	$SLOPE^2$	-0.0195*	-0.0401**
34	$THAHOR^2$	0.00102**	0.00174**
35	$DRAIN^2$	0.00785**	0.00666**
36	BIO^2	1.486**	1.537**
37	$PHMIN^2$	—	-1.681**
38	$DPHMIN^2$	-0.00126*	-0.00219**

[a] Rounded means and ranges of the variables from Table 4 are given in parentheses.

Table 20. (Continued)

X_i	Variate[a]	Regression coefficients (b_i)	
		MODEL G-10	MODEL H-8
39	$DCMAX^2$	—	-0.000510*
40	PPT^2	-0.0257**	-0.0280**
41	$TEMP^2$	-0.636**	-1.304**
43	DEPTH*PH	4.549	—
45	*CLAY	0.803**	—
46	*BD	-0.637**	—
47	*PEDISED	-8.49**	-14.59**
48	*TILL	—	-16.29**
49	*COLLUV-L	-12.18**	-13.14**
50	*ALLUV-L	-5.43**	-9.37**
51	*ALLUV-T	-8.11**	-16.73**
52	*EOLIAN	-22.48**	-27.32**
53	*SLOPE	1.613**	1.685**
54	*THAHOR	0.102**	0.142**
55	*DRAIN	-0.231**	-0.197**
56	*BIO	-54.96**	-53.89**
57	*PHMIN	—	-1.727*
58	*DPHMIN	-1.551**	-1.521*
59	*DCMAX	-0.233*	-0.166++
60	*PPT	1.485**	0.327**
61	*TEMP	-8.847**	3.058**
63	$DEPTH^2$*PH	-7.614**	—
65	*CLAY	-0.516*	—
66	*BD	0.744**	—
74	*SLOPE	-1.560**	-1.503**
77	*BIO	66.98**	64.82**
79	*DPHMIN	2.902**	3.129**
80	*DCMAX	0.211**	0.203**
81	*PPT	-0.917*	—
82	*TEMP	7.601**	—
94	$DEPTH^3$*BIO	-24.13**	-23.65**
96	*DPHMIN	-1.450**	-1.574**
	Intercept	-22.92*	-12.67
	R^2	0.673**	0.640**

final models which include interactions between all variables. In these models, the linear or quadratic effects of variables, other than DEPTH, on STP are modified by an interaction or interactions with DEPTH. The effect of DEPTH on STP, however, is a cubic function modified by linear*linear, quadratic*linear, or cubic*linear interactions with the other variables. The complex effect of DEPTH on STP will be discussed last.

<u>ALLUV-L</u> The ALLUV-L variable had a linear effect on STP modified by one interaction, the DEPTH*ALLUV-L interaction. The partial derivative of STP with respect to ALLUV-L in MODEL G-10 (Table 20) is dSTP/dALLUV-L = 9.62 - 5.43 DEPTH. As DEPTH increased from 0.20 to 1.20 meters (8 to 47 in.), the slope of the STP response to ALLUV-L soils varied from 8.5 to 3.1 pp2m P per unit change of ALLUV-L (Figure 11A). Because of the 0 or 1 coding for ALLUV-L, the ALLUV-L soils thus had 8.5 to 3.1 pp2m more P than the average of all other soils at depths in the profile from 0.20 to 1.20 m deep.

<u>DCMAX</u> This variable had a linear effect on STP modified by two interactions, the DEPTH*DCMAX and DEPTH^2*DCMAX interactions, in MODEL G-10 (Table 20). The dSTP/dCMAX = 0.0379 - 0.233 DEPTH + 0.211 DEPTH^2. Substitution of DEPTH values from 0.20 to 1.20 m into the partial derivative gives the slopes (rates of change of STP per unit change of DCMAX) of the linear response of STP on DCMAX at various depths in the profile. This varied from -0.0003 at 0.20 m, to a minimum of -0.0264 at 0.552 m, to 0 at 0.906 m, and then to 0.0621 at 1.20 m (Figure 11B). Thus, the linear effect of DCMAX on STP at various depths in the profile varied curvilinearly with increasing depth in the profile.

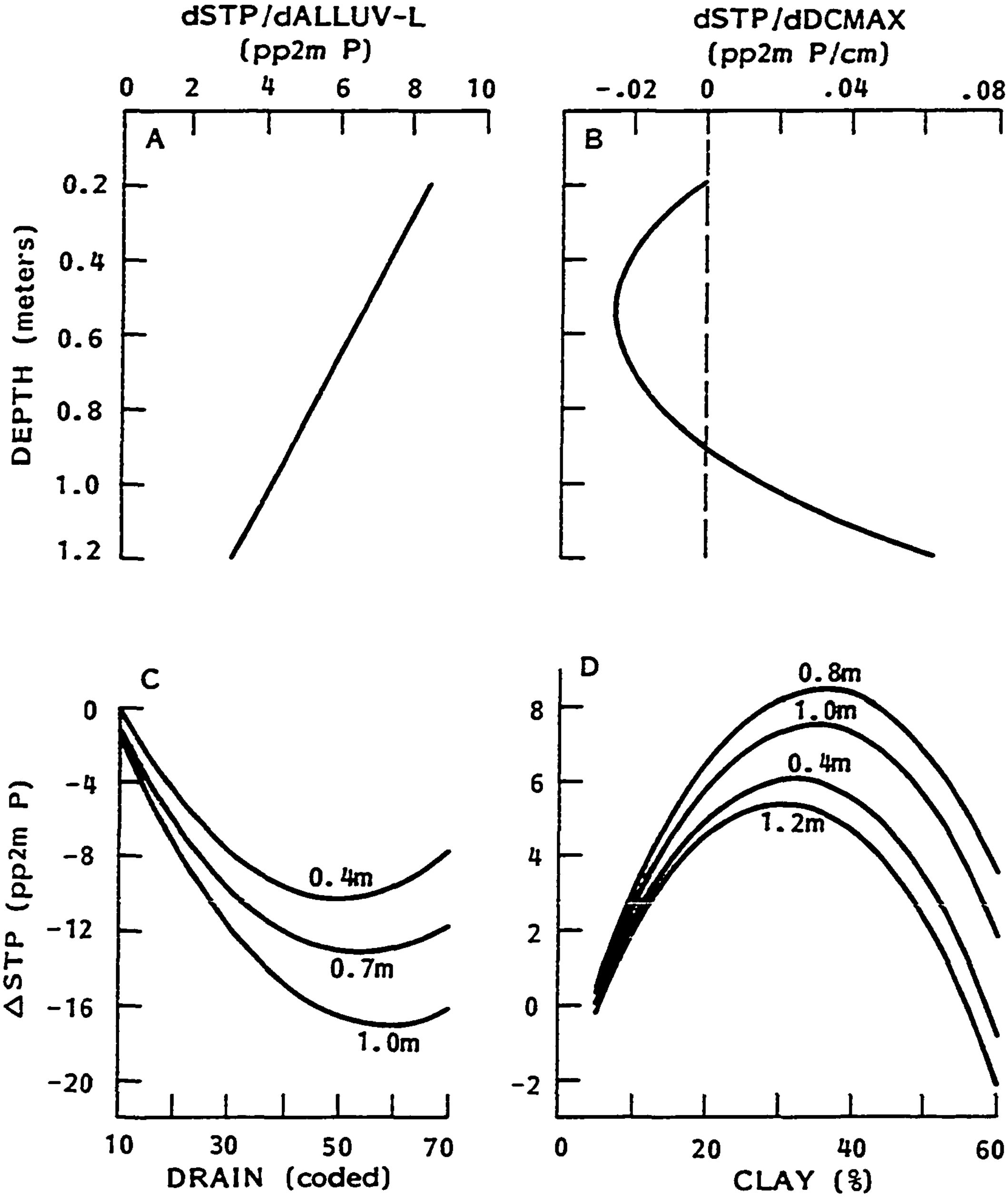

Figure 11. Change in the slope of the STP response with depth on (A) ALLUV-L and (B) DCMAX, and change in STP (ΔSTP) with (C) DRAIN and (D) CLAY

The depth in the soil profile associated with the minimum slope of change in STP on DCMAX can be obtained from the above partial derivative of STP with respect to DCMAX because it is a quadratic function of DEPTH. The derivative of this partial derivative with respect to DEPTH is: $d(dSTP/dDCMAX)/dDEPTH = -0.233 + 0.422\ DEPTH$. Setting the derivative = 0 and solving for DEPTH gives 0.552 m, the DEPTH where the minimum slope of the STP response on DCMAX occurred.

These varying responses of STP to increasing DCMAX (depth to maximum clay) show that in the upper profile from 0.20 to 0.906 m (8 to 36 in.) deep, the STP level decreased as DCMAX decreased. In the lower part of the profile deeper than 0.906 m, the STP increased as DCMAX increased. Because increasing DCMAX is associated with increasing soil development, the STP is then decreased in the upper profile as DCMAX increases but is increased in the deeper profile as DCMAX increases. Thus, the sigmoid STP distribution became more marked as DCMAX increased (within the limits of this model which contains no other interactions with DCMAX).

<u>DRAIN</u> This variable had a quadratic effect on STP modified by one interaction, DEPTH*DRAIN, in both models. The dSTP/dDRAIN (MODEL H-8, Table 20) = $-0.584 + 0.01332\ DRAIN - 0.197\ DEPTH$. As DEPTH increased from 0.20 to 1.20 m, the DRAIN associated with STPMIN shifted linearly from 47 (moderately well to somewhat poor) to 62 (somewhat poor to poor).

The changes in STP (ΔSTP) at three depths as coded DRAIN was increased (drainage became poorer) are shown in Figure 11C. The ΔSTP are changes relative to DEPTH = 0.40 m and DRAIN = 10 (excessive); they do not show the total differences in STP levels among depths in the profile. The changes in STP (ΔSTP) from DRAIN = 10 to the coded DRAIN associated with STPMIN were larger at DEPTH = 1.00 m (39 in.) than at DEPTH = 0.40 m (16 in.). From the coded DRAIN associated with the STPMIN to DRAIN = 80 (poor to very poor), the ΔSTP were larger at the 0.40 than at the 1.00 m depth (Figure 11C).

<u>PPT and TEMP</u> Both of the climatic variables, PPT and TEMP, had quadratic effects on STP modified by linear*linear interactions with DEPTH in MODEL H-8 (Table 20). The dSTP/dPPT = 0.883 - 0.0560 PPT + 0.327 DEPTH. As DEPTH increased from 0.20 to 1.20 m, the PPT associated with STPMAX shifted from 17 to 23 cm (decoded, from 80 to 86 cm or 31.4 to 33.8 in.). In the upper part of the profile at 0.40 m deep, STPMAX occurred at decoded PPT = 81 cm (31.9 in.), but at 1.00 m deep in the profile, STPMAX occurred at decoded PPT = 84.6 cm (33.3 in.).

The dSTP/dTEMP = 2.932 - 2.608 TEMP + 3.058 DEPTH. As DEPTH increased from 0.20 to 1.20 m, the TEMP at STPMAX shifted from 1.4 to 2.5 °C (decoded, from 8.4 to 9.5 °C or 47.1 to 49.1 °F).

Because both PPT and TEMP had quadratic effects on STP modified by the linear interaction with DEPTH, they had similar patterns as DRAIN on STP (Figure 11C) except that their patterns were inverted, having values associated with STPMAX instead of with STPMIN as DRAIN had. Higher levels of PPT and TEMP (greater rainfall and warmer temperatures) were associated with STPMAX in the lower profile than in the upper profile. Changes in STP from increasing PPT and TEMP were also greater in the lower than in the upper profile. These climatic effects are associated with soil weathering and development; higher levels of PPT and TEMP are required to get maximum STP levels in the lower than in the upper profile.

CLAY The CLAY variable had a quadratic effect on STP modified by two interactions, DEPTH*CLAY and $DEPTH^2$*CLAY. The dSTP/dCLAY (MODEL G-10, Table 20) = 0.311 - 0.0175 CLAY + 0.803 DEPTH - 0.516 $DEPTH^2$. Substitution of DEPTH values of 0.20 to 1.20 m into the partial derivative gave a series of simplified partial derivatives containing only the CLAY variable. When these were set = 0 and solved, the CLAY values that gave STPMAX changed curvilinearly from 25.7% at DEPTH = 0.20 m, to 35.6% at DEPTH = 0.78 m (31 in.), and to 30.3% at DEPTH = 1.20 m. Thus, the CLAY value at STPMAX varied in a quadratic manner with increasing DEPTH because of the presence of the quadratic*linear $DEPTH^2$*CLAY interaction.

The effects of the interactions between CLAY and both DEPTH and $DEPTH^2$ on the ΔSTP due to increasing levels of CLAY at four depths in the profile are shown in Figure 11D. All ΔSTP are changes relative to DEPTH = 0.40 m and CLAY = 5%. The ΔSTP as CLAY increased from 5 to 60% were greater at 0.78 m (31 in.) than at 0.40 m (16 in.) deep. At depths greater than 0.78 m, the ΔSTP associated with increasing CLAY decreased with depth. Largest ΔSTP due to variations in CLAY occurred at depths ranging from 0.60 to 1.00 m (24 to 39 in.). The STPMAX occurred at higher clay at these depths than in the upper or lower part of the profile. Differences in ΔSTP were affected more by depth in the profile at high clay levels than at low clay levels (Figure 11D).

<u>DPHMIN</u> The DPHMIN variable (depth to minimum pH) had a quadratic effect on STP modified by interactions with DEPTH, $DEPTH^2$, and $DEPTH^3$ in both models. For MODEL H-8, Table 20, the dSTP/dDPHMIN = $0.469 - 0.00438\ DPHMIN - 1.521\ DEPTH + 3.129\ DEPTH^2 - 1.574\ DEPTH^3$. The slopes of the STP responses on DPHMIN levels thus varied with the cubic function of depth in the profile. Because the DPHMIN levels associated with STPMAX also varied with the cubic function of DEPTH, the minimum and maximum values of DPHMIN associated with the STPMAX levels at various depths in the soil profile can be computed from the partial derivative of the above partial derivative with respect to DEPTH, which is: $d(dSTP/dDPHMIN)/dDEPTH = -1.521 + 6.258\ DEPTH - 4.722\ DEPTH^2$. Setting this derivative = 0 and solving with the quadratic formula gives the minimum and maximum DPHMIN values associated with STPMAX at depths in the profile of 0.32 m (13 in.) and 1.00 m (39 in.), respectively.

Substitution of DEPTH values from 0.20 to 1.20 m into the partial derivative of STP with respect to DPHMIN gave a series of simplified partial derivatives including only the DPHMIN variable. When these were set = 0 and solved, the DPHMIN values associated with STPMAX at DEPTH = 0.20, 0.32, 0.40, 0.60, 0.80, 1.00, and 1.20 m were 63, 57, 60, 78, 102, 115, and 98 cm, respectively. The DEPTH values associated with the minimum and maximum DPHMIN values that gave STPMAX occurred in the same zones in the profile where minimum and maximum STP levels usually have occurred in the soils with sigmoid P distributions with depth.

The effects of DPHMIN on ΔSTP at various depths in the soil profile are shown in Figure 12. From the regression statistics of MODEL H-8,

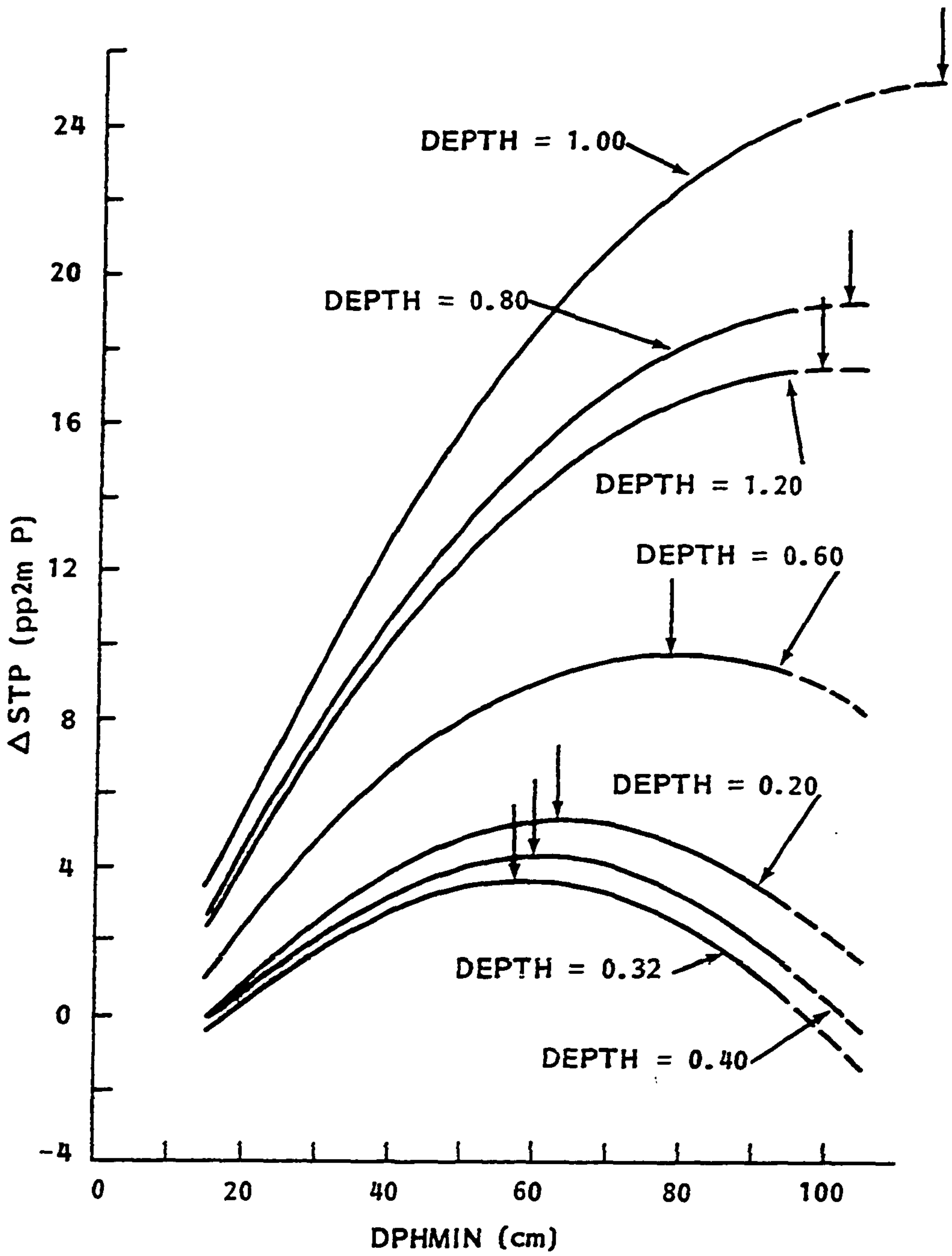

Figure 12. Effect of DPHMIN on ΔSTP at various depths in the profile (vertical arrows show DPHMIN values associated with STPMAX)

ΔSTP = 0.469 DPHMIN - 0.00219 DPHMIN^2 - 1.521 DEPTH*DPHMIN + 3.129 DEPTH^2*DPHMIN - 1.574 DEPTH^3*DPHMIN. When various values for DEPTH were substituted into this ΔSTP equation, a series of simplified ΔSTP equations were obtained from which ΔSTP were computed and plotted in Figure 12. The computed value for DEPTH = 0.20 m and DPHMIN = 15 was set = 0; all others are relative to this value. At DEPTH = 0.20 m (8 in.) the ΔSTP were small with increasing DPHMIN; at DEPTH = 0.32 m, the ΔSTP were even less and DPHMIN at STPMAX decreased. Then, as DEPTH increased, the ΔSTP with increasing DPHMIN up to DEPTH = 1.00 m became larger and the DPHMIN at STPMAX increased (became deeper in the profile). Below DEPTH = 1.00 m, ΔSTP and DPHMIN at STPMAX then decreased. These changes thus show the influence of weathering on DPHMIN and its influence on STP distributions.

<u>DEPTH</u> The DEPTH variable in the final MODELS G-10 and H-8 (Table 20) had a cubic effect on STP modified by linear*linear (DEPTH*X_i) interactions with most other variables, quadratic*linear (DEPTH^2*X_i) interactions with several variables, and cubic*linear (DEPTH^3*X_i) interactions with two variables. If the partial derivative of STP with respect to DEPTH is computed in order to determine the slope of the STP response on DEPTH at any DEPTH, many interactions with other variables affect these values. For example, the partial derivative of STP with respect to DEPTH in MODEL H-8 (Table 20) includes 3 terms for the cubic function of DEPTH, 15 terms for the DEPTH*X_i interactions, 4 terms for the DEPTH^2*X_i interactions, and 2 terms for the DEPTH^3*X_i interactions.

A linear*linear DEPTH*X_i interaction affects the slope of the STP response on DEPTH at any constant DEPTH in a linear manner as the level of the interacting variable is changed. The DEPTH*X_i interaction will affect the initial slope at the intercept (DEPTH = 0), will not affect the curvilinear rate of change of STP per unit increase in DEPTH, but will shift up or down the DEPTH values associated with STPMIN in the upper profile and the STPMAX in the lower profile, depending on the sign of the DEPTH*X_i interaction. Addition of the $DEPTH^2$*X_i and $DEPTH^3$*X_i interactions have more complex effects; they affect the slope of the STP response on DEPTH at any constant DEPTH in a quadratic or cubic manner and they affect the curvilinear rate of change of STP per unit increase in DEPTH.

From the partial derivative of STP with respect to DEPTH, the effects of 1 or 2 variables on the slopes of the STP response on DEPTH can be determined by setting all other variables at constant levels. The simplified partial derivative then can be used to determine the effects of the 1 or 2 variables on the STP response to DEPTH. If the level of any of the other variables is changed, the values of the simplified partial derivative are changed resulting in somewhat different relationships.

Another method to study the effect of the cubic function of DEPTH on STP level modified by one or more interactions with another variable is to simplify the regression equation. This is done by substituting constant values for all other variables in the equation except for the one whose interaction or interactions with DEPTH is to be studied. After substituting these constant values into the equation and multiplying them by their appropriate regression coefficients, the terms are collected. The simplified regression equation at fixed levels of other variables will contain the variates for the cubic function of DEPTH, linear or quadratic function of the interacting variable, and the interaction or interactions between DEPTH and the variable. From the simplified regression equation, the STP distributions with depth in the profile for different levels of the second variable can be computed and plotted. The partial derivatives of the series of simplified equations of STP on DEPTH at selected levels of the interacting variable also can be used to calculate the depths associated with the STPMIN and the STPMAX values.

Three examples of the effects of other variables on the depth distributions of STP will be presented. These will illustrate the effects of 1, 2, and 3 interactions between DEPTH and DRAIN, DEPTH and SLOPE, and DEPTH and BIO, respectively, on STP. The regression equation, MODEL H-8, was simplified using constant values for the other variables as follows: all parent material variables = 0 (parent material = LOESS), SLOPE = 2%, THAHOR = 30 cm, DRAIN = 40 (moderately well), BIO = 5 (prairie), PHMIN = 1.0 (pH = 5.5), DPHMIN = 50 cm, DCMAX = 60 cm, PPT = 25 (decoded, 88 cm or 35 in.), and TEMP = 2.0 (decoded, 9.0 °C or 48 °F). These values represent deep loess soils in east central Iowa.

The simplified equation for the effects of DEPTH and DRAIN on STP levels was: $STP = 37.39 - 63.96\ DEPTH + 144.12\ DEPTH^2 - 63.95\ DEPTH^3 - 0.584\ DRAIN + 0.00666\ DRAIN^2 - 0.197\ DEPTH*DRAIN$. Only a linear*linear interaction between DEPTH and DRAIN occurred in this example. From the simplified partial derivatives of STP with respect to DEPTH, the depth to STPMIN in the upper part of profile increased from 0.29 to 0.36 m and the depth to STPMAX decreased from 1.21 to 1.14 m as coded DRAIN increased from 20 to 80.

The STP distributions with depth at different drainage classes are shown in Figure 13. In the upper profile, the STP levels were lower for coded DRAIN = 40 (moderate well) and 50 (somewhat poor) than for DRAIN = 30 (well) or 70 (poor). In the lower profile, STP levels were highest in the well-drained soil and lowest in the somewhat poorly-drained and poorly-drained soils. Greater differences in STP levels among drainage classes were expected. The comparisons are somewhat unrealistic because the other variables were held at constant levels. The typical soils with this range in drainage, such as the Port Byron, Tama, Muscatine, and Garwin series, would vary some in THAHOR, SLOPE, PHMIN, DPHMIN, and DCMAX, all of which have interactions with DEPTH on STP levels.

The simplified equation for the effects of DEPTH and SLOPE on STP levels was: $STP = 24.31 - 75.21\ DEPTH + 147.13\ DEPTH^2 - 63.95\ DEPTH^3 + 0.271\ SLOPE - 0.0401\ SLOPE^2 + 1.685\ DEPTH*SLOPE - 1.503\ DEPTH^2*SLOPE$. Linear*linear and quadratic*linear interactions between DEPTH and SLOPE occurred in this example. The STP distributions with depth at different site slopes are shown in Figure 14. In the upper 0.8 m of the profile, STP levels were similar at SLOPE = 0 and 18% and also at SLOPE = 6 and 12%. Below 0.8 m, the STP levels differed, particularly between SLOPE = 0 and 18%. These differences show the effect of the $DEPTH^2*SLOPE$ interaction on STP and its effect on STP was most marked in the deeper

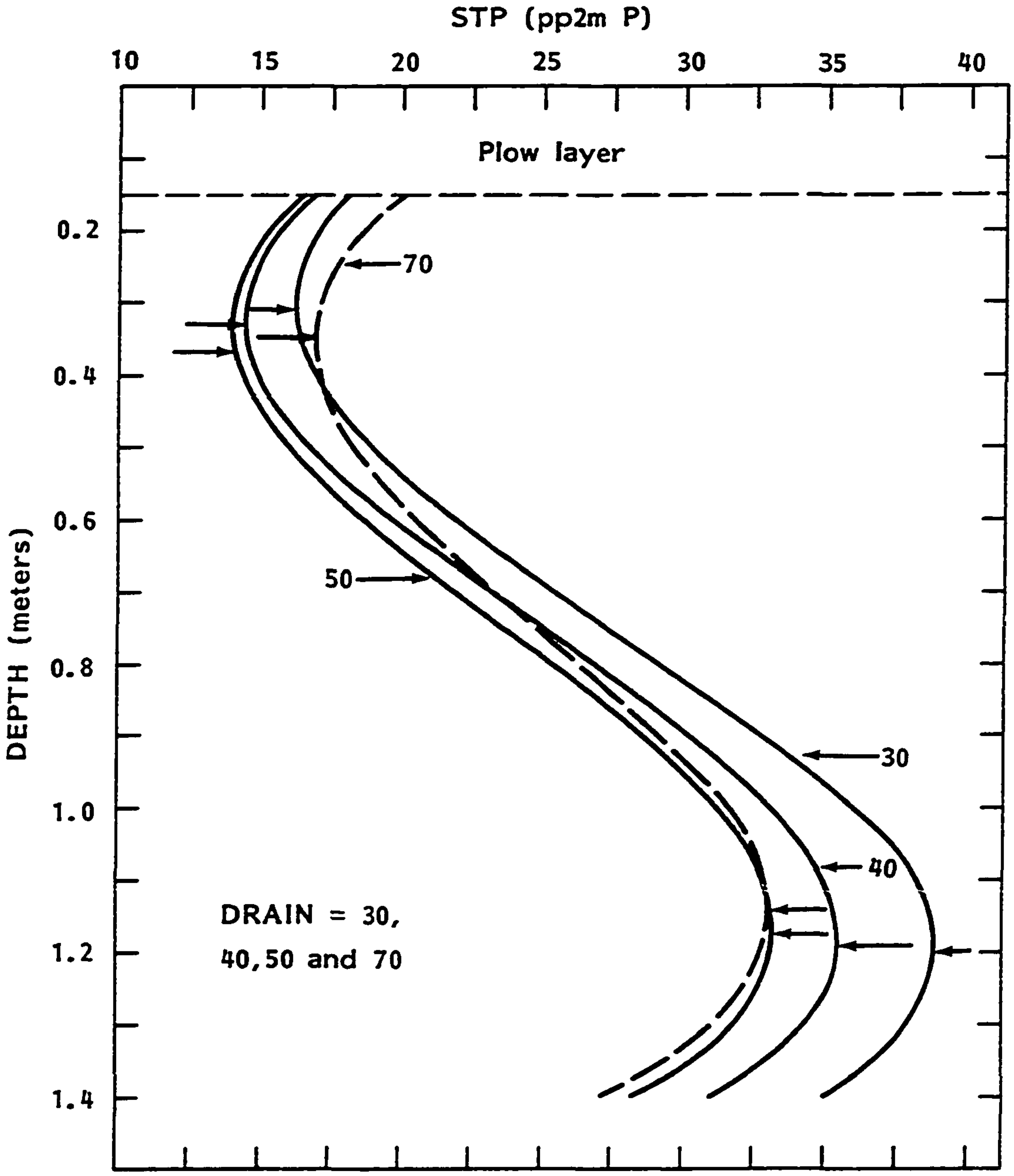

Figure 13. Soil test P distributions with depth for various soil drainage classes (unnumbered arrows show STPMIN and STPMAX levels)

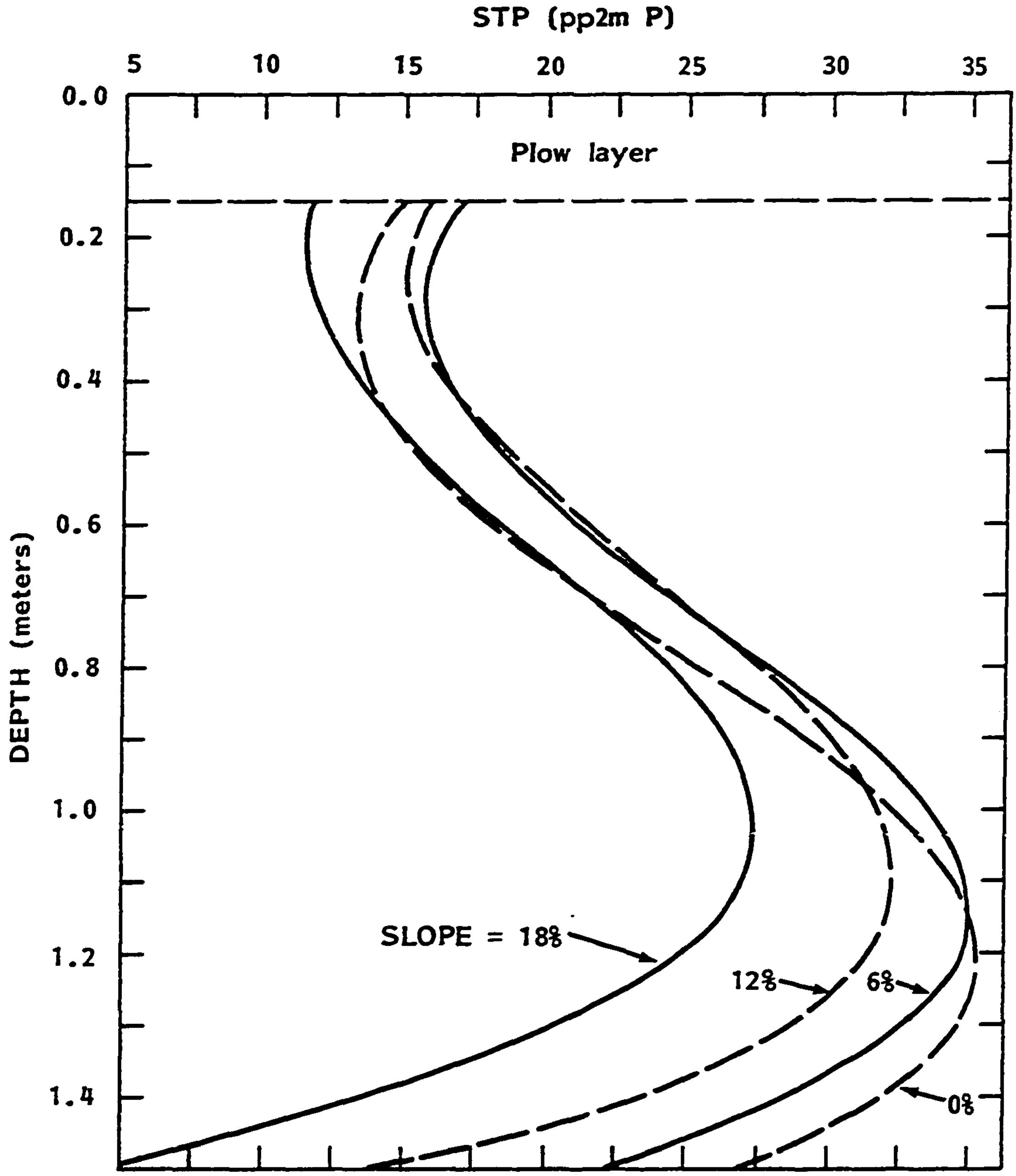

Figure 14. Soil test P distributions with depth for various site slopes

subsoil.

The effects of the DEPTH, $DEPTH^2$, and $DEPTH^3$ interactions with another variable on STP distributions are given by the simplified equation for the effect of DEPTH and BIO on STP level: STP = 1.66 + 197.61 DEPTH - 179.98 $DEPTH^2$ + 54.30 $DEPTH^3$ - 3.080 BIO + 1.537 BIO^2 - 53.89 DEPTH*BIO + 64.82 $DEPTH^2$*BIO - 23.65 $DEPTH^3$*BIO. The STP distributions with depth for BIO = 1 (forest), BIO = 3 (transition), and BIO = 5 (prairie) are shown in Figure 15. As was shown previously, the STP levels for the forest soil were highest and those for the prairie were least.

The linear, quadratic, and cubic interactions of DEPTH with BIO are shown in Figure 15 by the different STP distributions with depth. The prairie soil had the typical sigmoid STP distribution with STPMIN occurring at DEPTH = 0.32 m (13 in.) and STPMAX at DEPTH = 1.19 m (47 in.). The forest-prairie transition had a quadratic STP distribution with STPMAX also at 1.19 m. The forest soil had a rapidly increasing STP level in the upper subsoil with the absolute STPMAX at 1.18m; but the STP level, however, was almost the same between 0.9 to 1.4 m deep.

<u>Summary of MODELS G and H series</u>

Because of the wide variations in the subsoil distributions of soil test P (STP) in Iowa subsoils with profile depth, ranging from marked sigmoid to decreasing patterns, many interactions between the linear, quadratic, and cubic functions of depth with the other variables needed to be tested and selected to improve the prediction model.

For these models and all subsequent ones, the climatic variables

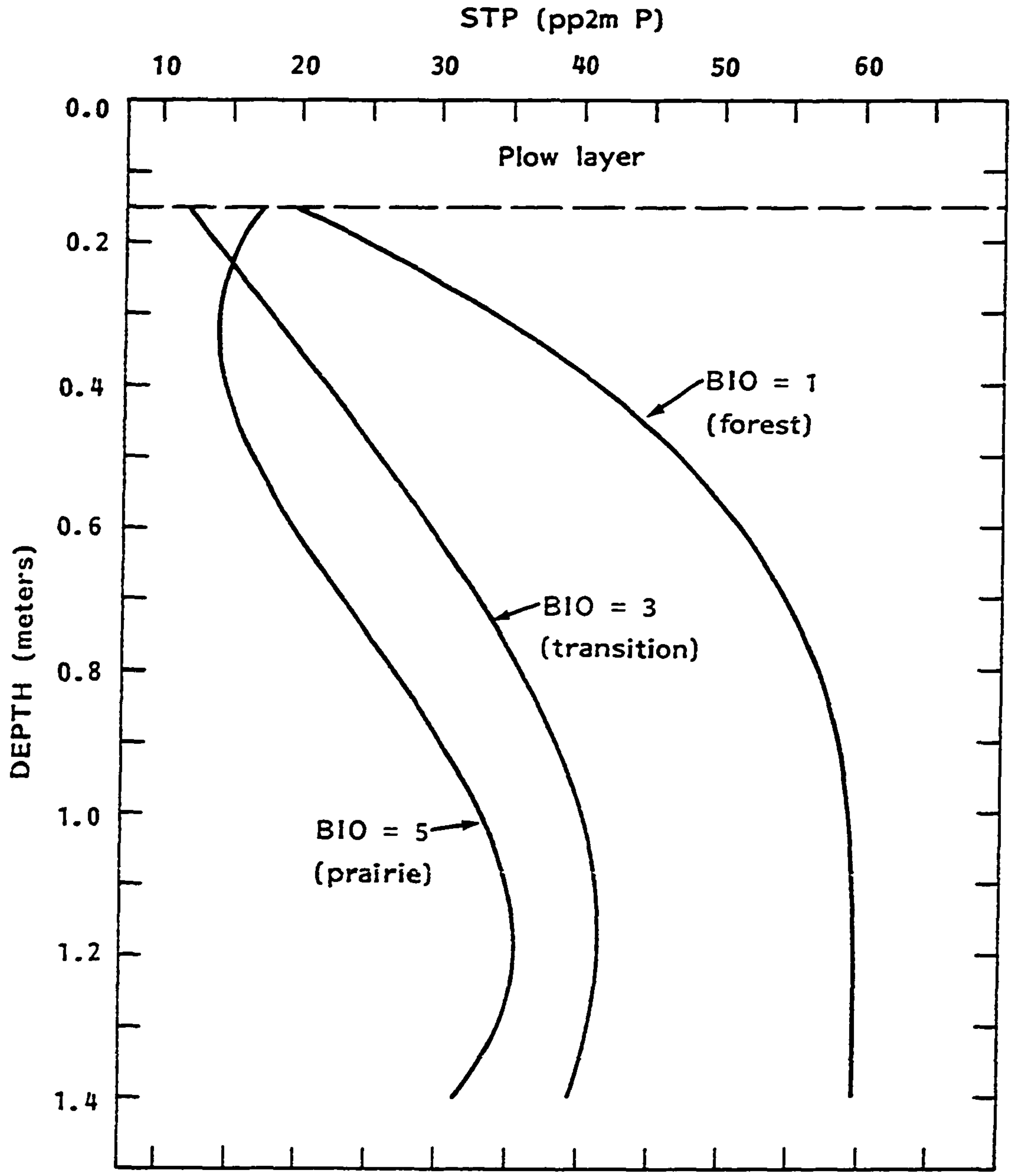

Figure 15. Soil test P distributions with depth for the biosequence of forest, transition, and prairie

were included and the location variables were deleted; also, the GHP variable was deleted from these models. For the MODEL G series, the significant variates in MODEL C-23 were included as the base set plus the ALLUV-T, SLOPE, and DCMAX variables which were added for further testing. For the MODEL H series (horizon variables deleted), the significant variates in final MODEL E-15 were included as the base set and only $DEPTH^2$ and $DEPTH^3$ variates were added. To the base set of variates, all $DEPTH*X_i$ and $DEPTH^2*X_i$ and most $DEPTH^3*X_i$ interactions were added and tested for significance. For these and all subsequent models, the unit of the DEPTH variable was transformed from cm to meters.

To select the significant DEPTH interactions, the nonsignificant $DEPTH^3*X_i$ variates were deleted first, then the nonsignificant $DEPTH^2*X_i$ interactions were deleted next if the $DEPTH^3*X_i$ interactions were deleted previously, and then nonsignificant $DEPTH*X_i$ interactions were deleted if the $DEPTH^2*X_i$ interactions were deleted previously. If the higher-order DEPTH interaction with another variable was significant, the lower-order interaction was retained, regardless of its significance.

Addition of the ALLUV-T, SLOPE, and DCMAX variables and all of the significant interactions with DEPTH, $DEPTH^2$, and $DEPTH^3$ increased the R^2 of final MODEL G-10 with 57 variates to 0.673 from the R^2 of 0.605 in MODEL C-23. Addition of $DEPTH^2$, $DEPTH^3$, and all significant DEPTH, $DEPTH^2$, and $DEPTH^3$ interactions increased the R^2 of final MODEL H-8 with 48 variates to 0.640 from the R^2 of 0.546 in MODEL E-15.

In MODEL G-10, 2 of 14 $DEPTH^3*X_i$ interactions tested, 9 of 17

$DEPTH^2*X_i$, and 16 of 17 $DEPTH*X_i$ interactions had significant effects on STP, mostly at the 1% level. In MODEL H-8 (horizon variables deleted), 2 of 13 $DEPTH^3*X_i$, 4 of 15 $DEPTH^2*X_i$, and all 15 $DEPTH*X_i$ interactions tested were significant, mostly at the 1% level.

The effects of the other X_i variables on STP modified by one or more of the $DEPTH*X_i$, $DEPTH^2*X_i$, and $DEPTH^3*X_i$ interactions were illustrated using partial derivatives of STP with respect to X_i or by computing the ΔSTP values at selected levels of the X_i variable and DEPTH. If a linear effect of X_i was modified by (1) the $DEPTH*X_i$ interaction, or (2) the $DEPTH*X_i$ and $DEPTH^2*X_i$ interactions, the partial derivative of STP with respect to X_i (slope of the linear STP response on X_i) varied linearly or curvilinearly (in a quadratic manner), respectively, with increasing DEPTH.

If the X_i variable had a quadratic effect on STP modified by (1) the $DEPTH*X_i$ interaction, (2) the $DEPTH*X_i$ and $DEPTH^2*X_i$ interactions, or (3) the linear, quadratic, and cubic interactions of DEPTH and X_i, both the magnitudes of the quadratic responses of STP on X_i and changes in the X_i associated with STPMIN or STPMAX varied in a linear, quadratic, or cubic manner, respectively, with increasing DEPTH.

Because the DEPTH variable had a cubic effect on STP modified by many interactions with other variables, the partial derivative of STP with respect to DEPTH had many terms. For example, dSTP/dDEPTH in MODEL H-8 included 3 terms for the cubic function of DEPTH, 15 terms for the $DEPTH*X_i$, 4 terms for the $DEPTH^2*X_i$, and 2 terms for the $DEPTH^3*X_i$ interactions. The effects of 1 or 2 variables on the slopes of the STP response on DEPTH in the partial derivative can be determined by setting all other variables at constant levels and using the simplified partial derivative to determine the effects of the selected variables on the STP response to DEPTH.

Another method to study the effect of the cubic function of DEPTH on STP level, modified by one or more interactions with another variable, is to simplify the regression equation by substituting constant values for all other variables, multiplying them by their appropriate regression coefficients, and collecting terms. The simplified regression equation at fixed levels of other variables contains the cubic function of DEPTH, the linear or quadratic function of the interacting variable, and all interactions between the two.

The effects of DEPTH and an interacting X_i variable with 1, 2, or 3 interactions between DEPTH and X_i on STP were illustrated, using simplified regression equations. The effects of DEPTH on STP modified by (1) the linear, (2) the linear and quadratic, or (3) the linear, quadratic, and cubic DEPTH interactions with X_i were, respectively, as follows: (1) the DEPTH*X_i interaction modified the initial slope of the STP response on DEPTH, the DEPTH values associated with both STPMIN and STPMAX, and magnitudes of STP levels with increasing DEPTH due to the influence of the interacting variable, but gave similar curvilinearity of the cubic function of STP on DEPTH at various X_i levels; (2) the DEPTH*X_i and $DEPTH^2$*X_i interactions had the same effects as in (1) above except that the coefficient of the $DEPTH^2$ variate was changed as X_i varied, which varied the curvilinearity of the cubic function of STP on

DEPTH and caused marked contrasts between STP differences in the upper and deeper profile; and (3) all three interactions with DEPTH caused marked changes in the distributions of STP with DEPTH because the coefficient of the $DEPTH^3$ variate also varied with level of X_i. For example, in the presence of all three interactions between DEPTH and BIO, the prairie soil had a typical cubic (sigmoid) STP distribution with DEPTH, the forest-prairie soil had higher STP levels but with a quadratic distribution with DEPTH, but the forest soil had even higher STP levels with a rapidly increasing STP level in the upper subsoil but a nearly constant STP level between 0.9 to 1.4 m deep, a STP distribution similar to an exponential response curve.

Multiple Regressions of STP on Selected Variates, Interaction MODELS J to M Series

To develop a final regression model of STP on selected variates from all variables, the MODELS J to M series of interaction models were computed. In preliminary MODELS J and K, selected interactions between variables other than DEPTH were added to the significant variates of final MODEL G-10, used as the base set of variates for both models. The most significant interaction variates from MODELS J and K were selected by stepwise, backward elimination and then combined and tested in the MODEL L series. For the final MODEL M series, nine interaction variates that were deleted from MODELS J and K in the final selection stages were added for further testing to those selected in the MODEL L series. The final STP prediction equation then was selected.

Preliminary interaction models, MODELS J to L series

The possible interactions between variables other than the DEPTH variable were 123 interactions. The 57 selected variates from final MODEL G-10 were used as the base set of variates to test and select these other interactions. There was space for testing only 40 additional interactions in the regression model because of the 100-variate capacity of the Helarctos II program (99 variates plus 1 dummy variate for the 51st transformation).

From the 123 possible interactions between variables, 78 were selected for testing in MODELS J and K after examining all of the interactions tested by Salih (1979). Interaction variates were included if they were significant in either final model for predicting STP1 in the upper profile layer (30-51 cm deep) or STP2 in the lower profile layer (76-107 cm deep) or if they had significance at the 15% level prior to deletion from the final models. Selection of interactions with the climatic variables was based on the significance of the interactions with the location variables in the previous study. Others were deleted because of limited range in the variable, such as slope of alluvium parent material, clay and drainage of eolian parent material, drainage of colluvium, and biosequence of some parent materials.

The 78 interactions were randomly divided between MODELS J and K and combined with the base set of 57 variates from final MODEL G-10. The variates included in the MODELS J and K series, the first and second preliminary models, are listed in Tables 21 and 22, respectively.

The model selection steps in both MODELS J and K are given in

Table 21. Variates included in the first preliminary model to select interactions between variables other than with the DEPTH variable, MODEL J series

X_i[a]	Variate	X_i	Variate	X_i[a]	Variate
2	PH	33	DEPTH*PH	66	STK*BD
3[b]	STP	34	*CLAY	67	*PPT
4	STK	35	*BD	68	*TEMP
5	CLAY	36	*PEDISED	69	CLAY*BD
6	BD	37	*COLLUV-L	71	*SLOPE
		38	*ALLUV-L	72	*THAHOR
7	PEDISED	39	*ALLUV-T	73	*BIO
8	COLLUV-L	40	*EOLIAN	74	*DCMAX
9	ALLUV-L	41	*SLOPE	75	*PPT
10	ALLUV-T	42	*THAHOR	76	BD*SLOPE
11	EOLIAN	43	*DRAIN	77	*BIO
		44	*BIO	78	*DCMAX
12	SLOPE	45	*DPHMIN		
13	THAHOR	46	*DCMAX	79	PEDISED*DRAIN
14	DRAIN	47	*PPT	80	*BIO
15	BIO	48	*TEMP	81	*TEMP
16	DPHMIN			82	ALLUV-L*DPHMIN
17	DCMAX	49	$DEPTH^2$*PH	83	*DCMAX
18	PPT	50	*CLAY	84	ALLUV-T*DRAIN
19	TEMP	51	*BD	85	*DCMAX
		52	*SLOPE	86	*PPT
20	DEPTH	53	*BIO	87	EOLIAN*BIO
21	$DEPTH^2$	54	*DPHMIN		
22	$DEPTH^3$	55	*DCMAX	88	SLOPE*DRAIN
		56	*PPT	89	*DPHMIN
23	PH^2	57	*TEMP	90	*TEMP
24	$CLAY^2$			91	THAHOR*BIO
25	BD^2	58	$DEPTH^3$*BIO	92	*DPHMIN
26	$SLOPE^2$	59	*DPHMIN	93	*PPT
27	$THAHOR^2$				
		60	PH*PEDISED	94	DRAIN*DPHMIN
28	$DRAIN^2$	61	*COLLUV-L	95	*DCMAX
29	BIO^2	62	*ALLUV-L	96	*PPT
30	$DPHMIN^2$	63	*THAHOR	97	*TEMP
31	PPT^2	64	*BIO	98	BIO*PPT
32	$TEMP^2$	65	*DPHMIN	99	PPT*TEMP

[a]X1, DEPTH in cm, was transformed to X20, DEPTH in m, for these and all later analyses; X70 was the dummy variable (51st transformation) in the Helarctos program.

[b]X3, STP, was the dependent variable.

Table 22. Varieties included in the second preliminary model to select interactions between variables other than with the DEPTH variable, MODEL K series

X_i	Variate	X_i	Variate	X_i	Variate
2	Same as	72	CLAY*ALLUV-L	86	ALLUV-L*PPT
to	listed for	73	*ALLUV-T	87	ALLUV-T*BIO
59	MODEL J	74	*DRAIN	88	*DPHMIN
		75	*DPHMIN		
60	PH*CLAY	76	*TEMP	89	SLOPE*THAHOR
61	*BD			90	*BIO
62	*ALLUV-T	77	BD*DRAIN	91	*PPT
63	*EOLIAN	78	*DPHMIN	92	THAHOR*DRAIN
64	*DRAIN	79	*PPT	93	*TEMP
65	*PPT	80	*TEMP		
66	*TEMP			94	DRAIN*BIO
		81	PEDISED*SLOPE	95	BIO*DPHMIN
67	STK*CLAY	82	*THAHOR	96	*DCMAX
68	*DRAIN	83	*DPHMIN	97	*TEMP
69	*BIO	84	*PPT	98	DPHMIN*DCMAX
71	*DCMAX	85	ALLUV-L*DRAIN	99	DCMAX*PPT

Table 23. Rigid selection of the interaction variates was needed to reduce the total number in both models to fit the available spaces for the next selection process in the MODEL L series. Also, no attempt was made at this stage to delete any of variates in the base set of variates. The interaction variates of X60 to X99 in both preliminary models (MODELS J and K) were tested and all interactions not significant at the 1% level and some just significant at 1% level were deleted stepwise. MODELS J-9 and K-8 were the final models. Deletion of 21 interaction variates from MODELS J-1 to J-9 and of 17 variates from MODELS K-1 to K-8 reduced the R^2 only slightly (Table 23). The R^2-values of final MODELS J-9 and K-8 were 0.734 and 0.751, respectively,

Table 23. Model selection steps, MODELS J and K series

Model no.	No. of X variates	Model selection steps	R^2
J-1	96	All variates listed in Table 21	.7368
2 to 5	91 to 80	Tested interaction variates X60 to X99; deleted all not significant at the 5% level stepwise from MODEL J-1	.7367 to .7356
6 to 9	79 to 75	Deleted variates not significant at the 1% level stepwise from MODEL J-5; MODEL J-9 was final model	.7351 to .7338
K-1	96	All variates listed in Table 22	.7539
2 to 4	90 to 83	Tested interaction variates X60 to X99; deleted all not significant at the 5% level stepwise from MODEL K-1	.7539 to .7534
5 to 8	81 to 79	Deleted variates not significant at the 1% level stepwise from MODEL K-4; MODEL K-8 was final model	.7528 to .7512

both considerably higher than the R^2 of 0.673 for MODEL G-10.

The most significant interaction variates, 18 from final MODEL J-9 and 22 from MODEL K-8, were then combined and tested in the MODEL L series. These interaction variates are listed in Table 24. The model selection steps for the MODEL L series are given in Table 25. Six interactions that had been significant in MODELS J-9 and K-8 were deleted in the model selection steps because of nonsignificance. One DEPTH interaction and, also, three squared variates were deleted because of nonsignificance (Table 25). The R^2 for final MODEL L-5 was 0.772, as compared with R^2-values of 0.734 and 0.751 for final MODELS J-9 and K-8, respectively.

Table 24. Selected interaction variates from MODELS J-9 and K-8 tested in the MODEL L series

X_i	Variate	X_i	Variate	X_i	Variate
2	Same as listed	72	CLAY*DCMAX	87	SLOPE*BIO
to	in Table 21	73	*PPT		
59	for MODEL J			88	THAHOR*DRAIN
		74	BD*DRAIN	89	*BIO
60	PH*CLAY	75	*BIO	90	*DPHMIN
61	*BD	76	*DPHMIN	91	*PPT
62	*BIO	77	*DCMAX	92	*TEMP
63	*PPT	78	*TEMP		
64	*TEMP			93	DRAIN*BIO
		79	PEDISED*SLOPE	94	*DCMAX
65	STK*BIO	80	*BIO	95	*PPT
66	*DCMAX	81	*TEMP		
67	*PPT	82	ALLUV-L*DRAIN	96	BIO*DPHMIN
68	*TEMP	83	*DPHMIN	97	*DCMAX
				98	*PPT
69	CLAY*BD	84	ALLUV-T*BIO	99	*TEMP
71	*ALLUV-T	85	*DPHMIN		
		86	*DCMAX	100	DCMAX*PPT

Table 25. Model selection steps, MODEL L series

Model no.	No. of X variates	Model selection steps	R^2
L-1	97	Initial model; all variates listed in Table 24	.7729
2 to 3	95 to 92	Deleted nonsignificant CLAY*PPT, PEDISED*TEMP, THAHOR*PPT, BIO*DCMAX, and BIO*PPT from MODEL L-1	.7729 to .7725
4	89	Deleted nonsignificant $SLOPE^2$, $DRAIN^2$, and $TEMP^2$ from MODEL L-3	.7724
5	88	Final model; deleted DEPTH*THAHOR from MODEL L-4	.7723

Final prediction model, MODEL M series

Model selection Because several interaction variates significant at the 5% to 1% levels had been deleted from preliminary interaction MODELS J-9 and K-8, they were retested in the MODEL M series. These variates are listed in Table 26. The variates in the initial model, MODEL M-1 (Table 27), included 88 variates from the final MODEL L-5 plus the 9 variates retested (Table 26).

Table 26. Interaction variates deleted from final MODELS J-9 and K-8 and then retested in the MODEL M series

Variate	t-value prior to deletion	Variate	t-value prior to deletion
PH*ALLUV-L	2.15*	ALLUV-T*DRAIN	-1.99*
*DRAIN	1.91++	EOLIAN*BIO	-2.74**
CLAY*DPHMIN	2.00*	SLOPE*THAHOR	-2.17*
PEDISED*THAHOR	2.28*	*DPHMIN	-2.63**
ALLUV-L*DCMAX	2.49*		

The model selection steps are given in Table 28. Of the 9 interactions retested, 5 were deleted; in addition, three interaction variates that had been significant in MODEL L-5 were also deleted. The instability of some variates in different mixes of variates reflected the intercorrelations among variables, although no variables were retained that were correlated greater than ±0.60. Henao (1976), however, reported some distortion and instability of the regression coefficients involving variables correlated between r = ±0.50 to r = ±0.60.

Table 27. Variates included in the multiple regression of STP on selected linear, quadratic, cubic, and interaction functions, final all-variable MODEL M series

X_i	Variate	X_i	Variate	X_i	Variate
2	PH	36	DEPTH*ALLUV-T	69	CLAY*DPHMIN
3	STP (Dep. var.)	37	*EOLIAN	71	*DCMAX
4	STK	38	*SLOPE		
5	CLAY	39	*DRAIN	72	BD*DRAIN
6	BD	40	*BIO	73	*BIO
		41	*DPHMIN	74	*DPHMIN
7	PEDISED	42	*DCMAX	75	*DCMAX
8	COLLUV-L	43	*PPT	76	*TEMP
9	ALLUV-L	44	*TEMP		
10	ALLUV-T			77	PEDISED*SLOPE
11	EOLIAN	45	DEPTH^2*PH	78	*THAHOR
		46	*CLAY	79	*BIO
12	SLOPE	47	*BD		
13	THAHOR	48	*SLOPE	80	ALLUV-L*DRAIN
14	DRAIN	49	*BIO	81	*DPHMIN
15	BIO	50	*DPHMIN	82	*DCMAX
16	DPHMIN	51	*DCMAX		
17	DCMAX	52	*PPT	83	ALLUV-T*DRAIN
18	PPT	53	*TEMP	84	*BIO
19	TEMP			85	*DPHMIN
		54	DEPTH^3*BIO	86	*DCMAX
20	DEPTH	55	*DPHMIN		
21	DEPTH^2			87	EOLIAN*BIO
22	DEPTH^3	56	PH*CLAY	88	SLOPE*THAHOR
		57	*BD	89	*BIO
23	PH^2	58	*ALLUV-L	90	*DPHMIN
24	CLAY^2	59	*DRAIN		
25	BD^2	60	*BIO	91	THAHOR*DRAIN
26	THAHOR^2	61	*PPT	92	*BIO
27	BIO^2	62	*TEMP	93	*DPHMIN
28	DPHMIN^2			94	*TEMP
29	PPT^2	63	STK*BIO		
		64	*DCMAX	95	DRAIN*BIO
30	DEPTH*PH	65	*PPT	96	*DCMAX
31	*CLAY	66	*TEMP	97	*PPT
32	*BD				
33	*PEDISED	67	CLAY*BD	98	BIO*DPHMIN
34	*COLLUV-L	68	*ALLUV-T	99	*TEMP
35	*ALLUV-L			100	DCMAX*PPT

Table 28. Model selection steps, final all-variable MODEL M series

Model no.	No. of X variates	Model selection steps	R^2
M-1	97	Initial model; all variates listed in Table 27	.7765
2 to 5	95 to 89	Deleted nonsignificant PH*DRAIN, BD*DCMAX, PEDISED*THAHOR, ALLUV-L*DCMAX, ALLUV-T*DRAIN, SLOPE*THAHOR, DRAIN*PPT, and BIO*DPHMIN variates from MODEL M-1	.7764 to .7756
6	88	Final model; deleted, $DPHMIN^2$ from MODEL M-5	.7755
7	86	Deleted $DEPTH^3*X_i$ interactions ($DEPTH^3*BIO$ and $DEPTH^3*DPHMIN$) from MODEL M-6	.7746
8	77	Deleted $DEPTH^2*X_i$ interactions (X45 through X53, Table 27) from MODEL M-7	.7631

The R^2 of 0.776 for final MODEL M-6 was only slightly higher than the R^2 of 0.772 for final MODEL L-5. The slight gain in R^2 from the additional MODEL M series probably was not worth the extra cost and time. To determine the value of the complex DEPTH interactions, the two highly significant $DEPTH^3*X_i$ interactions were deleted which reduced R^2 very slightly, and then the nine $DEPTH^2*X_i$ interactions were deleted which decreased the R^2 about 0.01 (Table 28).

The final prediction MODEL M-6 was developed by many steps to test and select the most significant linear, quadratic, and cubic functions of the variables plus interactions. To review these stages of model building or selection, the initial and final models of each series and their R^2-values are summarized in Table 29.

Table 29. Summary of the R^2-values and number of variates of selected models for the multiple regressions of STP on selected linear and quadratic functions and interactions of all variables

Model no.	No. of X variates	Model selection steps	R^2
A- 4	27	Linear model	.5791
A- 3	49	Initial complete prediction quadratic model	.6306
A- 8	37	Final complete prediction quadratic model (all variables included regardless of the correlation among them)	.6295
C- 1	49	Initial reduced prediction model	.6306
C-17	27	Final reduced prediction model (no variables correlated >±0.60)	.6129
C-23	25	Final reduced prediction model with GHP variable deleted	.6050
G- 1	79	Initial model of linear, quadratic, and cubic functions and interactions of DEPTH, $DEPTH^2$, and $DEPTH^3$ with all variables	.6753
G-10	57	Final model, deleted nonsignificant variates	.6726
J- 1	96	Initial model for first group of interactions	.7368
J- 9	75	Final model, deleting all variates not significant at the 1% level	.7338
K- 1	96	Initial model for second group of interactions	.7539
K- 8		Final model; deleting all variates not significant at the 1% level	.7512
L- 1	97	Initial model, combining variates from MODELS J-9 and K-8	.7729
L- 5	88	Final model, deleted ns variates	.7723

Table 29. (Continued)

Model no.	No. of X variates	Model selection steps	R^2
M- 1	97	Initial model after adding interactions from MODELS J and K for retesting to MODELS L-5	.7765
M- 6	88	Final all-variable prediction model	.7755

The addition of quadratic variates of all variables (except parent material) and the $DEPTH^3$ variate to the linear model of all variables increased the R^2 by about 0.05 (5%) (Table 29). Deletion of the highly correlated variables and the GHP variable in MODEL C-23 then reduced the R^2 about 0.025 (2.5%). Addition of the linear, quadratic, and cubic DEPTH interactions to the variates retained in MODEL C-23 increased the R^2 from 0.605 to 0.673 in final MODEL G-10 (Table 29). The interactions between the variables other than the DEPTH variable were added and tested in a series of models, the MODELS J to M series. These selected interactions increased the R^2-value from 0.673 in MODEL G-10 to 0.776 in the final MODEL M-6 (Table 29).

Interpretation of variable effects on STP, final MODEL M-6 The regression statistics for final MODEL M-6 are given in Table 30. The large number of significant interaction variates and the diverse effects of these variates on subsoil P levels in the final model show the complexity of the interrelationships among the variables on subsoil P distributions with depth.

Table 30. Regression statistics of STP on selected variates, final all-variable MODEL M-6

X_i	Variate[a]	b_i
2	PH (2.2; 0.4-3.8)	- 11.15**
4	STK (49; 10-370)	0.2705**
5	CLAY (29; 3-61)	0.4103**
6	BD (41; 18-81)	- 0.1300
7	PEDISED (—; 0-1)	- 8.35**
8	COLLUV-L (—; 0-1)	0.368
9	ALLUV-L (—; 0-1)	- 16.29*
10	ALLUV-T (—; 0-1)	- 10.57*
11	EOLIAN (—; 0-1)	- 15.90**
12	SLOPE (4; 0-20)	- 1.126**
13	THAHOR (34; 0-109)	- 0.4088**
14	DRAIN (44; 10-85)	- 1.351**
15	BIO (4.6; 1-5)	- 16.91**
16	DPHMIN (32; 15-94)	0.5401**
17	DCMAX (52; 18-122)	0.02227
18	PPT (17; 0-26)	0.5247*
19	TEMP (2; 0.2-3.8)	- 1.597
20	DEPTH (0.7; 0.15-1.4)	220.82**
21	$DEPTH^2$	-200.16**
22	$DEPTH^3$	75.26**
23	PH^2	- 0.9047**
24	$CLAY^2$	- 0.004890**
25	BD^2	- 0.002850*
26	$THAHOR^2$	0.001201**
27	BIO^2	0.7301**
29	PPT^2	- 0.01714**
30	DEPTH*PH	- 4.907^{++}
31	*CLAY	1.030**
32	*BD	- 1.468**
33	*PEDISED	- 5.962**
34	*COLLUV-L	- 11.08**
35	*ALLUV-L	- 7.389**
36	*ALLUV-T	- 6.064**
37	*EOLIAN	- 11.53**

[a]Rounded means and ranges from Table 4 are shown in parentheses.

Table 30. (Continued)

X_i	Variate	b_i	X_i	Variate	b_i
38	DEPTH*SLOPE	2.041**	69	CLAY*DPHMIN	0.004060**
39	*DRAIN	- 0.2627**	71	*DCMAX	-0.001873*
40	*BIO	-41.38**	72	BD*DRAIN	0.004533**
41	*DPHMIN	- 1.338**	73	*BIO	0.06657**
42	*DCMAX	- 0.1348+	74	*DPHMIN	-0.004484**
43	*PPT	2.145**	76	*TEMP	0.03863**
44	*TEMP	-14.83**			
			77	PEDISED*SLOPE	-0.5769**
45	$DEPTH^2$*PH	- 5.919**	79	*BIO	2.796**
46	*CLAY	- 0.4291*			
47	*BD	0.7273**	80	ALLUV-L*DRAIN	0.3229**
48	*SLOPE	- 1.934**	81	*DPHMIN	0.1758**
49	*BIO	47.10**			
50	*DPHMIN	2.494**	84	ALLUV-T*BIO	4.734**
51	*DCMAX	0.1637**	85	*DPHMIN	0.09392**
52	*PPT	- 1.200**	86	*DCMAX	-0.1110**
53	*TEMP	10.49**			
			87	EOLIAN*BIO	5.378**
54	$DEPTH^3$*BIO	-16.69**			
55	*DPHMIN	- 1.190**	89	SLOPE*BIO	0.2404**
			90	*DPHMIN	-0.009210**
56	PH*CLAY	- 0.08876**			
57	*BD	0.2491**	91	THAHOR*DRAIN	0.001548*
58	*ALLUV-L	1.782*	92	*BIO	0.07313**
60	*BIO	2.470**	93	*DPHMIN	-0.006502**
61	*PPT	- 0.2748**	94	*TEMP	0.04826**
62	*TEMP	0.8514**			
			95	DRAIN*BIO	0.2246**
63	STK*BIO	- 0.04918**	96	*DCMAX	0.001913**
64	*DCMAX	0.000494**			
65	*PPT	0.003632**	99	BIO*TEMP	0.3942**
66	*TEMP	- 0.03634**	100	DCMAX*PPT	-0.004343**
67	CLAY*BD	- 0.009341**	--	Intercept	61.374**
68	*ALLUV-T	- 0.1551*	--	R^2	0.776**

The interactions between DEPTH and the other variables are listed in order in Table 30. Fifteen DEPTH*X_i, 9 $DEPTH^2$*X_i, and 2 $DEPTH^3$*X_i interactions were retained.

The interactions between the variables other than DEPTH are summarized in Table 31. The interactions are listed twice, once with each interacting variable. In MODEL M-6, the BIO variable was involved in 13 interactions; this was expected because biosequence has a dominant effect on subsoil P levels. The DPHMIN variable had 9 interactions and each of the PH and BD variables had 8 interactions (Table 31), which indicated the importance of these 3 variables for predicting STP. Each of the CLAY, DCMAX, and TEMP variables was associated with 7 interactions; the DRAIN variable had 6 interactions. The variables that had 5 interactions were SLOPE, ALLUV-T, and PPT. Each of the STK, ALLUV-L, and THAHOR variables had 4 interactions; the PEDISED variable had 3 interactions; the EOLIAN variable had 2 interactions; and the COLLUV-L variable had 1 interaction.

To examine the variable effects on STP distributions, two methods were used. In the first one, the partial derivative of STP with respect to the X_i variable of interest in final MODEL M-6 was used to show its effect on STP. This gave the slope of the STP response on the variable which was constant if the variable effect was linear but was not constant if the variable effect on STP was curvilinear. It is difficult to explain the effect of the variable of interest on the STP distribution with depth in the presence of several to many interactions. All variables have to be held at constant values except the one or two

Table 31. Summary of the variable effects in final all-variable MODEL M-6

Variable[a]	t-values of Linear	t-values of Squared	Interacting variables with listed variable and their signs[b]
PH	- 5.8**	-3.6**	-DEPTH, -$DEPTH^2$, -CLAY, +BD, +ALLUV-L, +BIO, -PPT, +TEMP
STK	5.8**	ns	-BIO, +DCMAX, +PPT, -TEMP
CLAY	2.7**	-4.1**	+DEPTH, -$DEPTH^2$, -PH, -BD, -ALLUV-T, +DPHMIN, -DCMAX
BD	- 0.9	-2.4*	-DEPTH, +$DEPTH^2$, +PH, -CLAY, +DRAIN, +BIO, -DPHMIN, +TEMP
PEDISED	- 3.5**	—	-DEPTH, -SLOPE, +BIO
COLLUV-L	0.2	—	-DEPTH
ALLUV-L	- 4.5**	—	-DEPTH, +PH, +DRAIN, +DPHMIN
ALLUV-T	- 2.0*	—	-DEPTH, -CLAY, +BIO, +DPHMIN, -DCMAX
EOLIAN	- 3.6**	—	-DEPTH, +BIO
SLOPE	- 3.7**	ns	+DEPTH, -$DEPTH^2$, -PEDISED, + BIO, -DPHMIN
THAHOR	- 4.4**	3.6**	+DRAIN, +BIO, -DPHMIN, +TEMP
DRAIN	-11.9**	ns	-DEPTH, +BD, +ALLUV-L, +THAHOR, +BIO, +DCMAX
BIO	- 9.5**	5.8**	-DEPTH, +$DEPTH^2$, -$DEPTH^3$, +PH, -STK, +BD, +PEDISED, +ALLUV-T, + EOLIAN, +SLOPE, +THAHOR, +DRAIN, +TEMP
DPHMIN	5.0**	ns	-DEPTH, +$DEPTH^2$, -$DEPTH^3$, +CLAY, -BD, +ALLUV-L, +ALLUV-T, -SLOPE, -THAHOR
DCMAX	0.6	ns	-DEPTH, +$DEPTH^2$, +STK, -CLAY, -ALLUV-T, +DRAIN, -PPT
PPT	2.4*	- 4.9**	+DEPTH, -$DEPTH^2$, -PH, +STK, -DCMAX
TEMP	- 1.3	ns	-DEPTH, +$DEPTH^2$, +PH, -STK, +BD, +THAHOR, +BIO

[a]Interactions of DEPTH, $DEPTH^2$, and $DEPTH^3$ are listed in order in Table 30.

[b]Significances of interactions are given in Table 30.

whose effect on STP is to be examined. The effects of many combinations of one or two variables on STP distributions can be examined in the same partial derivative, but this process is tedious if many interactions are present.

In the second method, the regression coefficients of the regression equation for final MODEL M-6 were programmed into the computer. Constant values were assigned to all variables in the equation except for the DEPTH variable and two others. For selected values of DEPTH and the other variables, the predicted STP values were computed for all combinations of levels of the variables and printed in the output. The predicted STP values then were plotted with depth for various combinations of the two variables.

This method has limitations because, as the fixed levels of the other variables are changed, the relationships among DEPTH and the two variables on STP will change to a varying degree. With so many interactions present in MODEL M-6, many combinations of DEPTH and two other variables will occur. Also, some combinations of levels of the variables are outside of the range of observed values; some do not occur such as high DPHMIN and low PPT levels or high BD levels associated with loess-derived soils. However, the logical trends of the variable effects on STP distributions can be illustrated if values of the variables held constant are carefully selected.

The effects of the variables on STP distributions will be discussed in the following subsections. Because of the large number of interactions, the effects of most variables on STP are involved in complex interrelationships. All of the interactions will not be discussed. To explain the most important interaction effects on STP, partial derivatives will be used and some interactions will be illustrated in figures using predicted STP values.

PH The partial derivative of STP with respect to PH is $dSTP/dPH = -11.15 - 1.809\ PH - 4.907\ DEPTH - 5.919\ DEPTH^2 - 0.0888\ CLAY + 0.249\ BD + 1.78\ ALLUV\text{-}L + 2.470\ BIO - 0.275\ PPT + 0.851\ TEMP$. Thus, the curvilinear effect of PH on STP, or the slope of the STP response on PH level, was modified by: two interactions with the quadratic function of DEPTH; positive interactions with BD, ALLUV-L, BIO, and TEMP; and negative interactions with CLAY and PPT.

To study the effect of PH on STP at two levels of the BD variable, the partial derivative was simplified by setting all other variables at constant levels, as follows: DEPTH = 1.0 m, CLAY = 30%, ALLUV-L = 0, BIO = 5 (prairie), PPT = 22 (decoded, 85 cm or 33.5 in.), and TEMP = 1.0 (decoded, 8 °C or 46.4 °F). The simplified partial derivative = $-17.84 - 1.809\ PH + 0.249\ BD$. At BD = 35 (deep loess soils) and BD = 70 (till soils), the partial derivative was simplified further to: $dSTP/dPH = -9.12 - 1.81\ PH$ and $dSTP/dPH = -0.41 - 1.81\ PH$, respectively. These two simplified derivatives gave the slopes of the STP response on PH level at two BD levels, at 1.0 m deep, and at fixed levels of all other variables interacting with PH. Both showed that STP decreased at an increasing rate as PH level was increased.

At PH = 0.5 (pH 5.0) and PH = 2.5 (pH 7.0), the slopes of the quadratic STP response to PH level were -10.03 and -13.65, respectively, for BD = 35 and -1.31 and -4.93, respectively, for BD = 70. From the products of the average slopes of -11.84 and -3.12 between the two PH points on the curve and the 2.0 unit change in PH, the ΔSTP values were calculated to be -23.7 and -6.2 pp2m P for BD = 35 and 70, respectively. Thus, the decrease in STP was considerably larger at 1.0 m deep in the prairie, deep loess-derived soils of northeastern Iowa than in the prairie till-derived soils in the same area as the soil pH increased from 5.0 to 7.0. This difference was because the STP levels were initially higher in the deep loess than in the till soils.

The effects of the interactions between PH, DEPTH, and BIO on predicted STP levels computed from final MODEL M-6 (Table 30) are shown in Figure 16. Other interacting variables were held constant as follows: STK = 40, CLAY = 30, BD = 40, all parent material variables = 0, SLOPE = 4, THAHOR = 25, DRAIN = 40, DPHMIN = 40, DCMAX = 50, PPT = 22, and TEMP = 2. The variables at these levels describe the deep loess-derived soils from the climatic conditions of east-central Iowa. The predicted STP distributions with DEPTH are shown in Figure 16 for combinations of three PH levels and the forest and prairie members of the biosequence (BIO = 1 and 5, respectively).

The STP levels in the forest soils decreased with increased PH levels at all depths in the profile, but the differences were larger in the lower than in the upper profile (Figure 16). In the prairie soils, the STP levels were similar in the upper profile but decreased increasingly with increased PH level with profile depth. These effects were accounted for by the DEPTH*PH and DEPTH^2*PH interactions. The cubic STP distribution with depth in the prairie soils and the apparent quadratic distribution in the forest soils were accounted for by the three

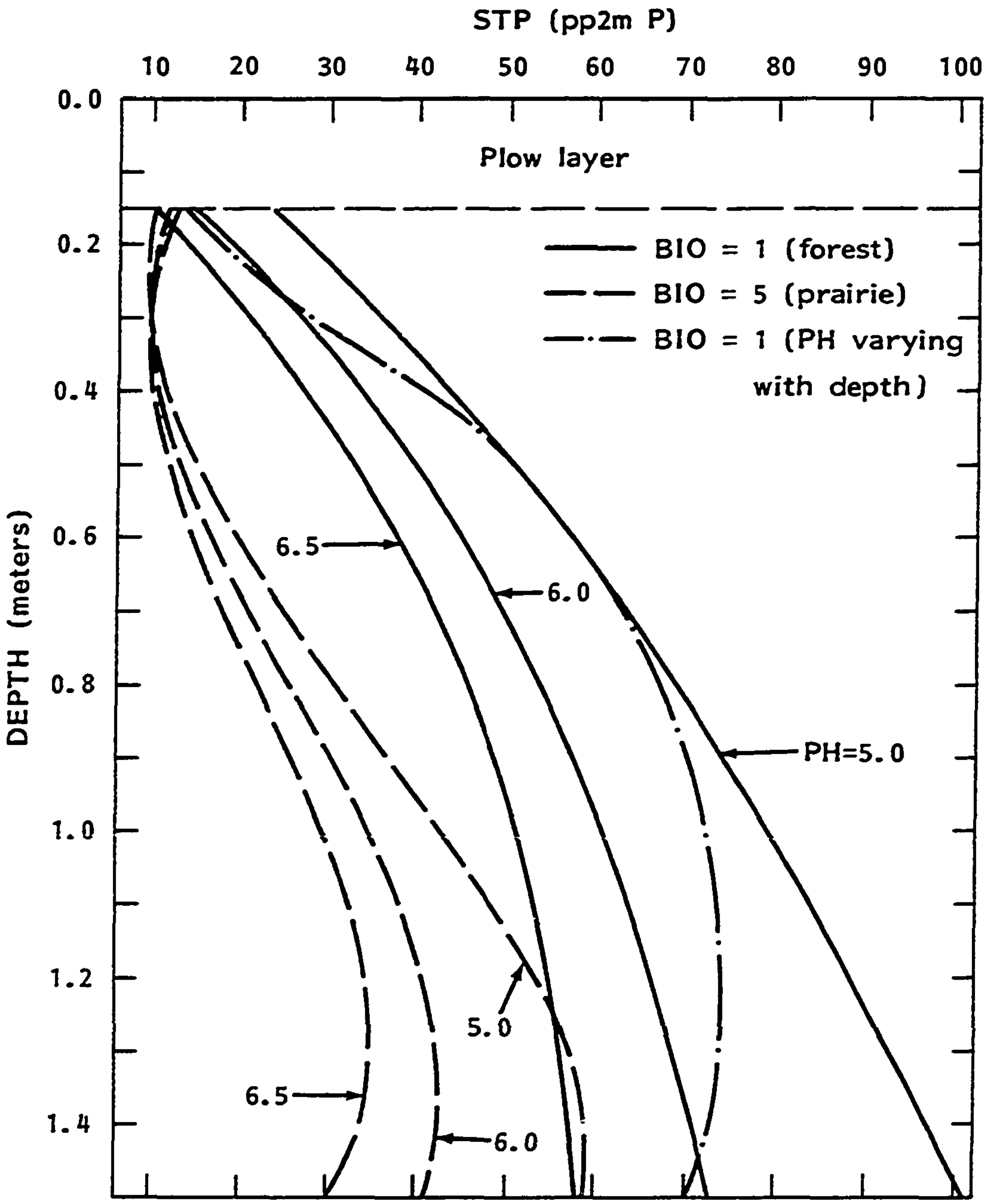

Figure 16. Predicted STP distributions with depth for decoded soil pH (PH) levels and two members of the biosequence (BIO)

interactions between the cubic function of DEPTH and BIO. The PH*BIO interaction also affected the STP distributions. The STP distributions in the transition soils (BIO = 3) were computed but not shown in Figure 16; these soils had intermediate STP distributions with depth.

The STP distributions with respect to PH levels in Figure 16 illustrate the general relationships; these distributions, however, are not very realistic because the PH levels were fixed at the same levels for all depths in the profile. The estimated STP values were computed for all combinations of 0.1 m increments of DEPTH, 0.5 increments of coded PH from 0 (pH 4.5) to 4 (pH 8.5), and five biosequence classes (1 to 5). From the large number of predicted STP values, the STP distributions can be plotted for any given soil pH distribution and biosequence class, including intergrades.

The predicted STP distribution of a forested profile is shown in Figure 16 by the dotted-dashed line; in this soil, the pH distribution decreased from pH 6.1 below the plow layer to 5.0 from 0.5 to 0.7 m deep and then increased to 6.1 at 1.5 m deep. The predicted STP distribution for a realistic pH distribution with depth thus was different from the one with a constant PH throughout the profile. As shown in Figure 16, this distribution was slightly sigmoid and had STPMAX higher in the profile than the corresponding forest soil with constant pH.

The effects of a wider range of soil pH values and the interaction between PH and PPT on STP distributions are shown in Figure 17. For these predicted values, the interacting variables were fixed at the same levels as for the PH, DEPTH, and BIO relationships except that

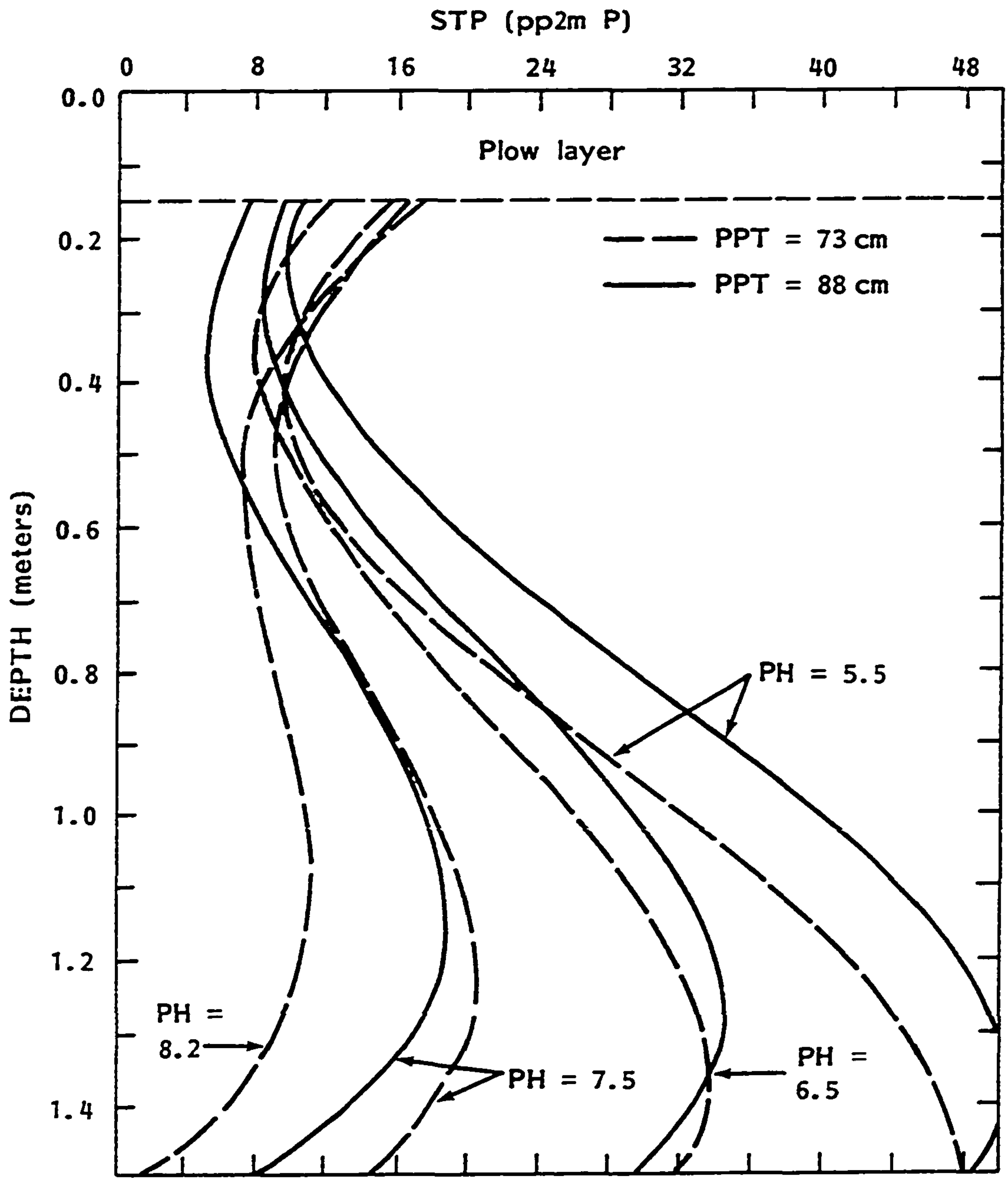

Figure 17. Predicted STP distributions with depth at various soil pH (PH) and mean annual precipitation (PPT) levels

BIO = 5 (prairie). The STP distributions are shown for soil pH levels of 5.5 to 8.2 and for two levels of PPT, 73 cm or 29 in. and 88 cm or 34.5 in.

The STP levels decreased markedly in the lower profile as soil pH increased from 5.5 to 8.2 but were not affected as much in the upper part of the profile. The negative interaction between PH and PPT showed that STP differences between PPT levels at most depths decreased as PH level increased. The reversal of the PPT effect at PH = 7.5 may have little significance because few soils in the 88 cm (34.5 in.) annual rainfall area of Iowa had such a high pH level at the constant levels used for the interacting variables. The negative correlations between PPT and the subsoil pH-related variables (Table 7) caused difficulty in interpreting the PH*PPT interaction over the entire range of both.

The interactions between PH and the other variables, such as CLAY, ALLUV-L, and TEMP, can be illustrated using the predicted STP values from MODEL M-6. The PH interactions with BD, BIO, and PPT which were discussed show the general effects of PH on STP distributions.

<u>STK</u> From MODEL M-6 (Table 30), the dSTP/dSTK = 0.270 - 0.0492 BIO + 0.000494 DCMAX + 0.00363 PPT - 0.0363 TEMP. The slope of the linear STP response to STK level was not affected by DEPTH; it decreased as BIO changed from forest to prairie and as TEMP increased and it increased as DCMAX and PPT increased. The STK effect on STP will not be discussed in detail; it is believed to be an associated effect rather than a cause and an effect.

CLAY From MODEL M-6 (Table 30), the dSTP/dCLAY = 0.410 - 0.00978 CLAY + 1.030 DEPTH - 0.429 DEPTH^2 - 0.0888 PH - 0.00934 BD - 0.155 ALLUV-T + 0.00406 DPHMIN - 0.00187 DCMAX. The curvilinear effect of CLAY on STP was modified by two interactions with the quadratic function of DEPTH, a positive interaction with DPHMIN, and negative interactions with PH, BD, ALLUV-T, and DCMAX. The interaction between CLAY and DEPTH on STP which was similar to that in MODEL G-10 was illustrated in Figure 11D. The positive CLAY*DPHMIN interaction showed that the positive effect on CLAY on STP and the CLAY level associated with STPMAX increased as DPHMIN increased. The negative interactions with PH, BD, ALLUV-T, and DCMAX showed that the effect of CLAY on STP decreased and the CLAY level at STPMAX decreased as the levels of each of these variables increased.

At DEPTH = 0.8 m, PH = 1.5, ALLUV-T = 0, DPHMIN = 40, and DCMAX = 50, the simplified dSTP/dCLAY with BD present = 0.894 - 0.00978 CLAY - 0.00934 BD. At coded BD = 35 (decoded 1.35 g/cm^3, loess soils) and 70 (decoded 1.7 g/cm^3, till soils), the slopes of the STP response on CLAY were 0.567 - 0.00978 CLAY and 0.240 - 0.00978 CLAY, respectively. At BD = 35 and BD = 70, STPMAX occurred at 58 and 25% CLAY, respectively. With low bulk density at 0.8 m deep (typical of loess soils) STP increased as CLAY increased throughout most of the observed CLAY range; with high bulk density (typical of till and alluvial terrace units), STP increased as CLAY increased to 25% and then decreased at higher CLAY levels.

The effects of the interactions between CLAY, DEPTH, and DPHMIN on predicted STP level computed from final MODEL M-6 are shown in Figure 18. Other interacting variables were held constant as was done in studying the interactions between PH, DEPTH, and BIO, except BIO = 5 (prairie) and PH = 1.5 (decoded, pH = 6.0). As CLAY increased from 20 to 40%, the STP levels increased at depths below 0.4 m. The STP differences between CLAY levels became larger as DPHMIN increased (Figure 18), because of the positive CLAY*DPHMIN interaction. The reversal of the CLAY level effects on STP above and below 0.3 to 0.4 m deep were accounted for by the DEPTH*CLAY and $DEPTH^2$*CLAY interactions.

<u>BD</u> The partial derivative (MODEL M-6, Table 30) = -0.130 - 0.00570 BD - 1.468 DEPTH + 0.727 $DEPTH^2$ + 0.249 PH - 0.00934 CLAY + 0.00453 DRAIN + 0.0666 BIO - 0.00448 DPHMIN + 0.0386 TEMP. The curvilinear effect of BD on STP was modified by two interactions with the quadratic function of DEPTH, positive interactions with PH, DRAIN, BIO, and TEMP, and negative interactions with CLAY, and DPHMIN. The positive interactions showed that the negative effects of BD on STP became less as PH, DRAIN, BIO, and TEMP levels increased; the negative interactions showed that the negative effects became greater as CLAY and DPHMIN levels increased. The negative CLAY*BD interaction was discussed previously in the CLAY subsection.

To illustrate the positive BD*BIO interaction, the partial derivative was simplified by setting DEPTH = 1.0 m, PH = 1.5, CLAY = 30, DRAIN = 40, DPHMIN = 40, and TEMP = 1.0 and was: dSTP/dBD = -0.736 - 0.0057 BD + 0.0666 BIO. At BIO = 1 and 5, the slopes of the STP response on the quadratic function of BD were -0.669 - 0.0057 BD and -0.403 -

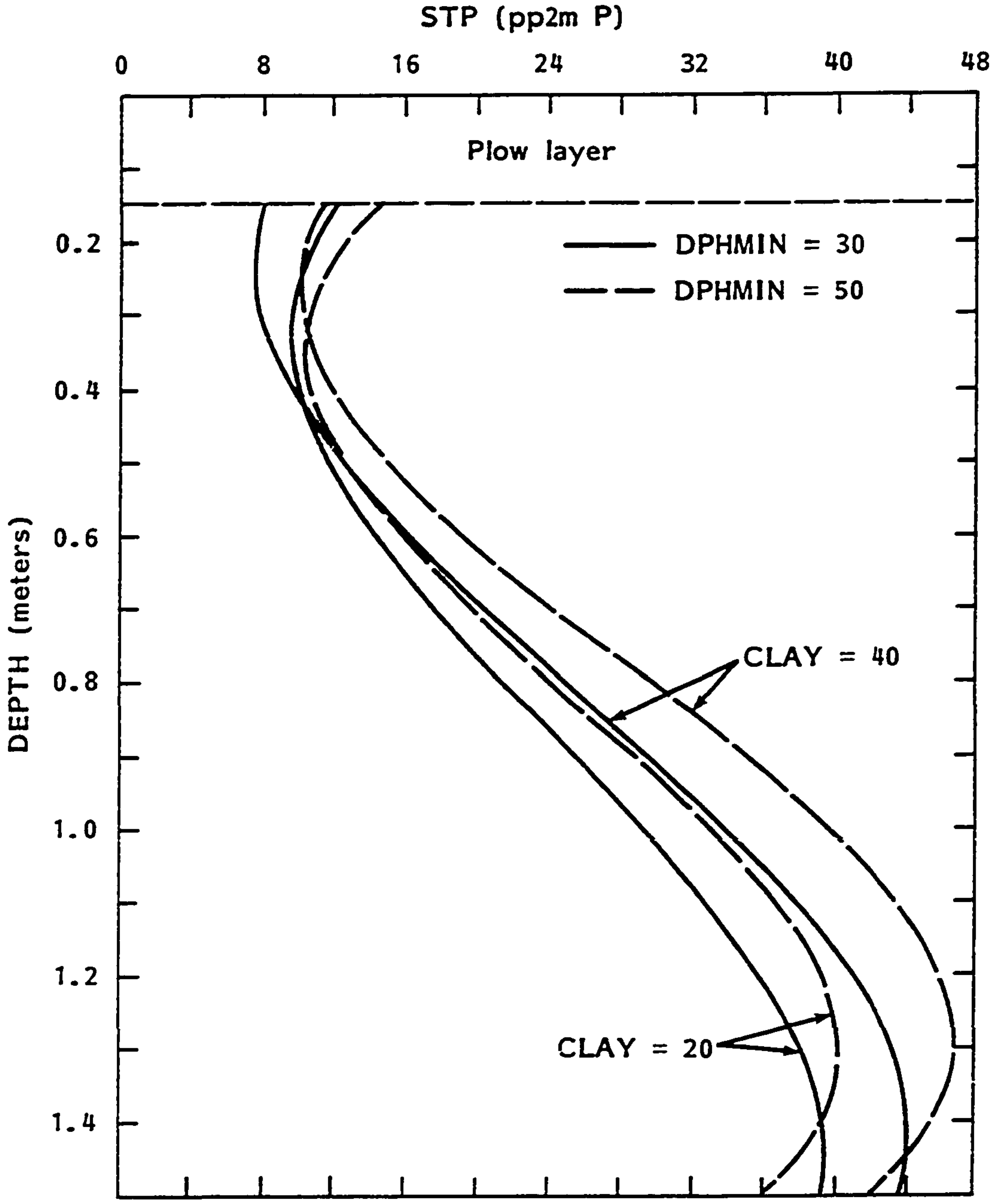

Figure 18. Predicted STP distributions with depth at two levels of percent clay (CLAY) and depth to minimum pH (DPHMIN)

0.0057 BD, respectively. The negative effect of increasing BD on STP was less in the prairie soils than in the forest soils, primarily because at low levels of BD (in loess soils), the STP levels were greater in the forest than in the prairie soils.

The effects of the interactions between BD, DEPTH, and DRAIN on predicted STP levels computed from final MODEL M-6 are shown in Figure 19. Other interacting variables were held constant, as follows: PH = 1.5, STK = 40, CLAY = 30, all parent material variables = 0, SLOPE = 4, THAHOR = 25, BIO = 5, DPHMIN = 40, DCMAX = 50, PPT = 22, and TEMP = 2.

As decoded BD increased from 1.3 to 1.8 g/cm^3 at DRAIN = 50, the STP levels decreased at all depths in the profile (Figure 19). From decoded BD = 1.3 to 1.7, the decreases in STP became less as coded DRAIN increased from 30 (well) to 70 (poorly drained) because of the positive BD*DRAIN interaction.

The BD distributions with profile depth do not vary as much in the loess-derived soils as in the till-derived soils (Dumenil, 1978). The STP distributions at the higher fixed BD levels of 1.7 and 1.8 in Figure 19 are distorted because the BD levels in the upper profile are considerably less than these values in the till-derived soils. Thus, these distributions are not realistic because BD was held constant throughout the profile. The distortions due to constant BD at BD = 1.3 and 1.5 are not as noticeable.

A realistic BD effect on the STP distribution is shown in the curve in Figure 19 for BD varying with depth (from 1.4 at 24 cm to 1.77 g/cm^3 at 120 cm deep). This STP distribution is more typical of the moderately

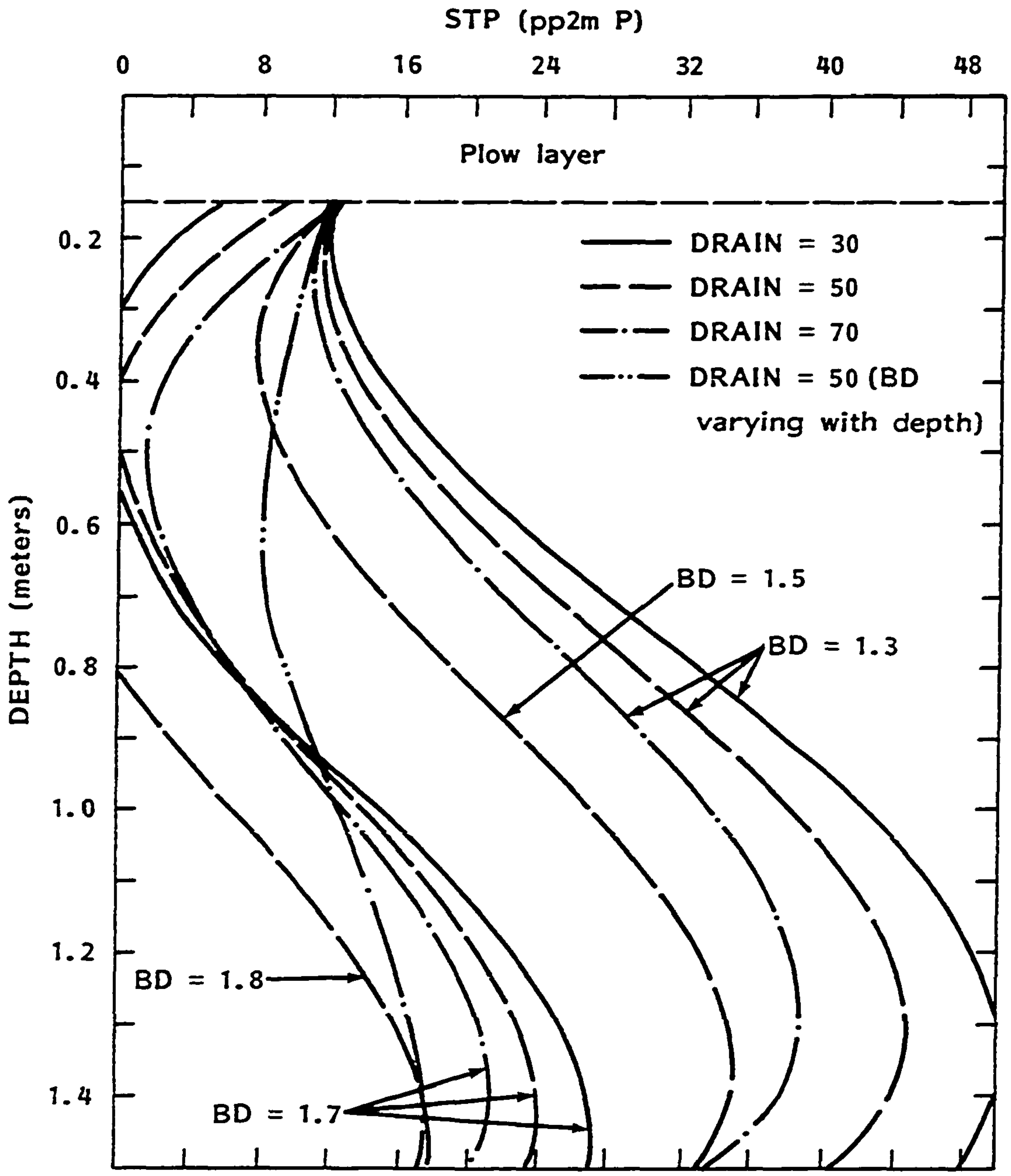

Figure 19. Predicted STP distributions with depth at various bulk density (BD) and drainage class (DRAIN) levels

well-drained, till-derived soils such as Kenyon. However, PH was held constant at 1.5 (decoded, 6.0) for computing the predicted STP values. If one visualizes the effect of increasing pH with depth on STP as in Figures 16 and 17, one can see how MODEL M-6 can predict a decreasing STP distribution with depth.

<u>PEDISED</u> The dSTP/dPEDISED (Table 30) = -8.35 - 5.96 DEPTH - 0.577 SLOPE + 2.80 BIO. Interactions show that the linear slope of the STP response on PEDISED became more negative as DEPTH and SLOPE increased and less negative as BIO changed from forest to prairie. At DEPTH = 0.8 m and SLOPE = 4%, the simplified partial derivative = -15.43 + 2.80 BIO. At BIO = 1 and 5, the slopes = -12.6 and -1.4, respectively. These indicated that PEDISED had 13 pp2m less P than all other parent materials at the 1.0 meter depth in the forest soils but only about 1 pp2m less P in the prairie soils.

<u>COLLUV-L</u> The dSTP/dCOLLUV-L = 0.37 - 11.1 DEPTH. The slope of the linear STP response on COLLUV-L became more negative as DEPTH increased. At DEPTH = 0.4 and 1.0 m, the slopes = -4.1 and -10.7, respectively. These indicated that COLLUV-L had 4 pp2m less P than the average of all other parent materials at the 0.4 m depth and about 11 pp2m less P at the 1.0 m depth.

<u>ALLUV-L</u> The dSTP/dALLUV-L (Table 30) = -16.29 - 7.39 DEPTH + 1.78 PH + 0.323 DRAIN + 0.176 DPHMIN. These interactions indicated that the linear slope of STP response on ALLUV-L became more negative or less positive as DEPTH increased and became more positive as PH, DRAIN, and DPHMIN increased. The negative DEPTH*ALLUV-L interaction

was shown in Figure 11A.

At DEPTH = 0.8 m, PH = 1.5, and DRAIN = 50, the simplified partial derivative = -3.3 + 0.176 DPHMIN. From DPHMIN = 30 to 60 cm, the slopes varied from 2.0 to 9.0 pp2m P/unit of ALLUV-L. These showed that ALLUV-L soils at 0.8 m depth had from 2 to 9 pp2m more P than the average of all other soils as DPHMIN increased from 30 to 60 cm deep.

Higher STP levels had been observed in some of the poorly-drained ALLUV-L soils than in the better-drained ones (Table 3). At DEPTH = 0.8 m, PH = 1.5, and DPHMIN = 40 cm, the simplified derivative = -12.4 + 0.323 DRAIN. As coded DRAIN increased from 30 to 70, the slopes increased from -2.7 to 10.2; these showed that predicted STP levels would be about 3 pp2m P less in the well-drained ALLUV-L soils than in all other well-drained soils and about 10 pp2m P more in poorly-drained ALLUV-L than in all other poorly-drained soils.

<u>ALLUV-T</u> From MODEL M-6 (Table 30), the dSTP/dALLUV-T = -10.6 - 6.06 DEPTH - 0.155 CLAY + 4.73 BIO + 0.094 DPHMIN - 0.111 DCMAX. These interactions showed that the slope of the linear STP response on ALLUV-T became more negative as DEPTH, CLAY, and DCMAX increased and became more positive as coded BIO and DPHMIN increased. The ALLUV-T soils, most of which were terrace units underlain by sand, were variable because one group was from northwestern Iowa and the other was from northeastern Iowa. The STP distributions varied in the two areas, primarily because of differences in PH and DPHMIN (Table 3).

At DEPTH = 0.8 m, CLAY = 25, BIO = 5, and DCMAX = 50, the simplified derivative = -1.3 + 0.094 DPHMIN. At DPHMIN = 25 (NW Iowa) and

50 (NE Iowa), the slopes = 1.0 and 3.4, respectively, which showed that the ALLUV-T soils at 0.8 m deep in NW and NE Iowa had 1.0 and 3.4 pp2m more P, respectively, than the average of all other soils at these DPHMIN levels.

<u>EOLIAN</u> The dSTP/dEOLIAN = -15.9 - 11.5 DEPTH + 5.4 BIO. These interactions showed that the slope of the linear STP response on EOLIAN parent material became more negative as DEPTH increased and less negative as BIO changed from forest to prairie soils. At DEPTH = 1.0 m, the simplified partial derivative = -27.4 + 5.4 BIO. At BIO = 1 and 5, the slopes = -22.0 and -0.4, respectively. These slopes show that forested EOLIAN parent material at the 1.0 m depth had 22 pp2m less P than all other forested parent materials, but prairie Eolian soils had only 0.5 pp2m less P than all other prairie soils. The large difference between forested EOLIAN and other parent materials was because of the high STP levels in the forested, deep loess-derived soils.

<u>SLOPE</u> In MODEL M-6 (Table 30), the dSTP/dSLOPE = -1.13 + 2.04 DEPTH - 1.93 DEPTH^2 - 0.58 PEDISED + 0.240 BIO - 0.00921 DPHMIN. The linear effect of SLOPE on STP was modified by two interactions with the quadratic function of DEPTH (shown previously in Figure 14), negative interactions with PEDISED and DPHMIN, and a positive interaction with BIO.

The effects of the interactions between SLOPE, DEPTH, and BIO on predicted STP levels computed from final MODEL M-6 are shown in Figure 20. Other interacting variables were held constant at the same values as were listed in the BD subsection except that BD = 40 and DRAIN = 40.

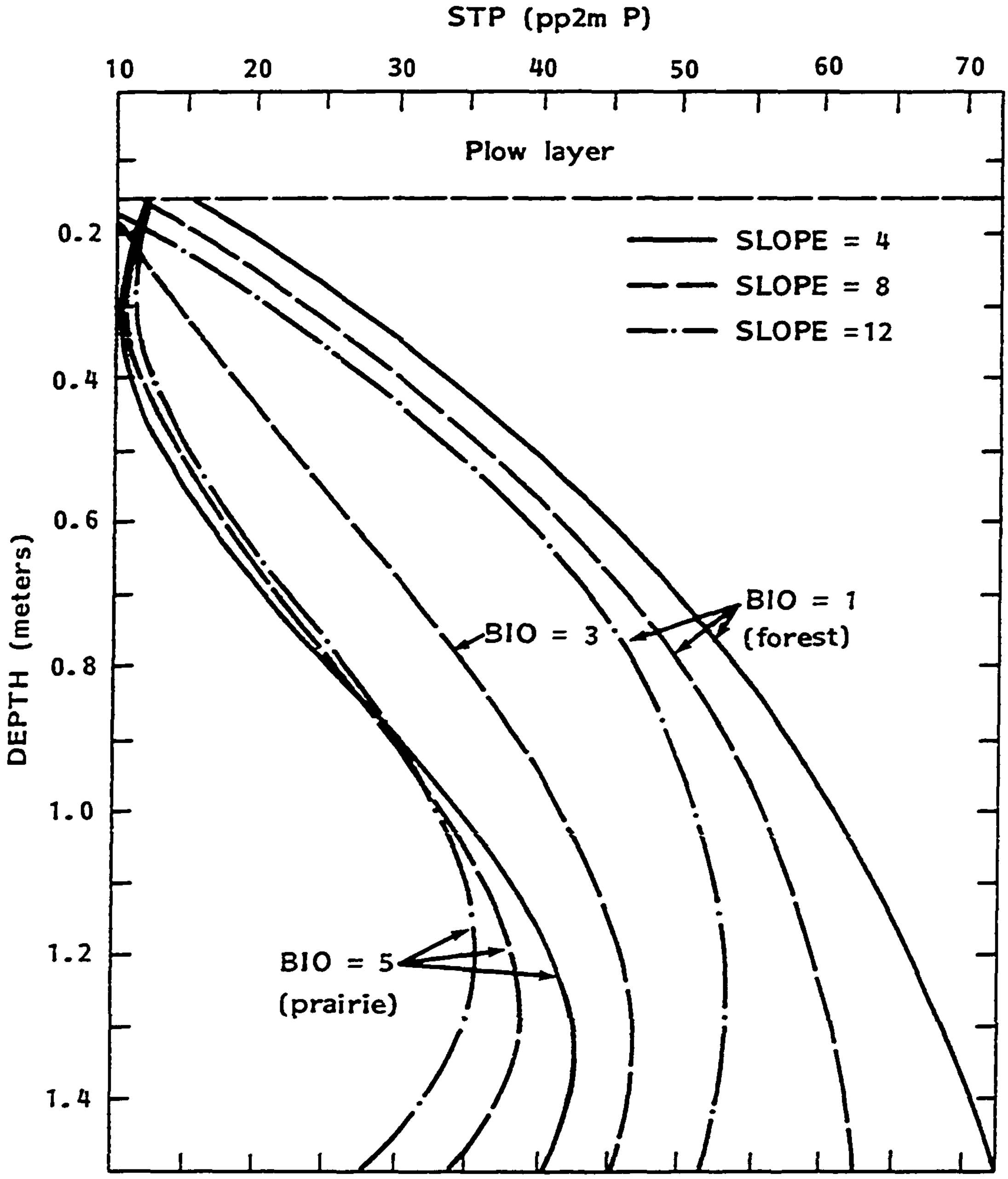

Figure 20. Predicted STP distributions with depth at various site slope (SLOPE) and biosequence (BIO) levels

The STP levels in the forest soils decreased with increased SLOPE at all depths in the profile, but decreases were larger in the lower than in the upper profile (Figure 20). In the prairie soils, the STP levels were similar in the upper profile but decreased below 1.0 m deep as slope increased. The different SLOPE effect on STP in the forest and prairie soils illustrates the SLOPE*BIO interaction.

THAHOR The dSTP/dTHAHOR (Table 30) = -0.409 - 0.00240 THAHOR + 0.00155 DRAIN + 0.0731 BIO - 0.00650 DPHMIN + 0.0483 TEMP. Thus, the curvilinear effect of THAHOR on STP was modified by positive interactions with DRAIN, BIO, and TEMP, and a negative interaction with DPHMIN. The THAHOR was one of the two variables that did not have an interaction with DEPTH.

The effects of the interactions between THAHOR, DEPTH, and TEMP on predicted STP levels are shown in Figure 21. Other interacting variables were held constant as follows: PH = 1.5, STK = 40, CLAY = 30, BD = 40, all parent material variables = 0, SLOPE = 4, DRAIN = 40, BIO = 5, DPHMIN = 40, DCMAX = 50, and PPT = 22. The variables at these levels describe the deep loess-derived soils from the climatic conditions of eastern Iowa.

As THAHOR increased from 0 to 40 cm (0 to 16 in.), the predicted STP levels decreased the same at all depths at either TEMP level (Figure 21) because no DEPTH*THAHOR interaction occurred. The differences in STP levels between THAHOR = 0 and 40 cm were larger at TEMP = 7.5 °C (northern Iowa) than at TEMP = 10.5 °C (southern Iowa) because of the THAHOR*TEMP interaction.

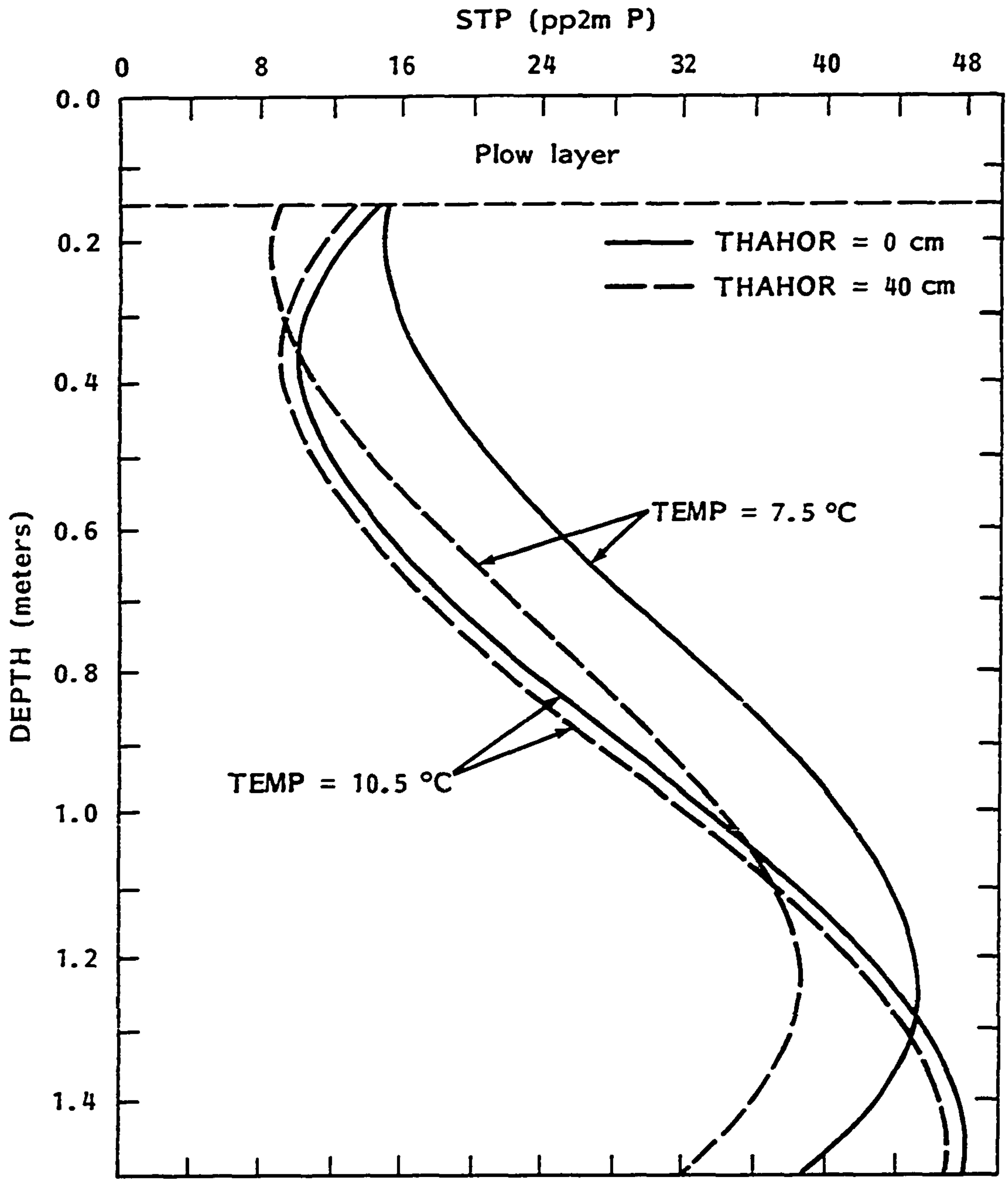

Figure 21. Predicted STP distributions with depth at various thickness of A horizon (THAHOR) and mean annual temperature (TEMP) levels

DRAIN From MODEL M-6 (Table 30), the dSTP/dDRAIN = -1.35 - 0.263 DEPTH + 0.00453 BD + 0.323 ALLUV-L + 0.00155 THAHOR + 0.225 BIO + 0.00191 DCMAX. The slopes of the linear STP response on DRAIN became more negative with DEPTH, less negative or more positive as BD, THAHOR, BIO, and DCMAX levels increased, and generally positive in the ALLUV-L parent material.

The effects of the interactions between DRAIN, DEPTH, and BD on predicted STP distributions were shown previously in Figure 19. At decoded BD = 1.3 (typical of loess-derived soils), STP decreased at all depths as coded DRAIN increased. The negative effect of DRAIN as it varied from 30 (well) to 70 (poor) became more negative with depth due to the negative DEPTH*DRAIN interaction. At decoded BD = 1.7 (till-derived soils), the negative effect of DRAIN on STP in the lower profile was less than in the soils with the lower BD level. This was due to the positive BD*DRAIN interaction. The reversal of the DRAIN effect in the upper profile at BD = 1.7 may be because BD is considerably less in the upper profile and not constant throughout as shown in Figure 19. This distortion effect on STP was discussed in the BD subsection.

The effects of the interactions between DRAIN, DEPTH, and BIO are shown in Figure 22. In the forest soils (BIO = 1), the predicted STP levels decreased markedly as coded DRAIN increased. The difference in STP between DRAIN = 30 and 50 in prairie soils was much less because of the positive DRAIN*BIO interaction.

BIO From final MODEL M-6 (Table 30), the dSTP/dBIO = -16.9 + 1.460 BIO - 41.38 DEPTH + 47.10 DEPTH^2 - 16.69 DEPTH^3 + 2.47

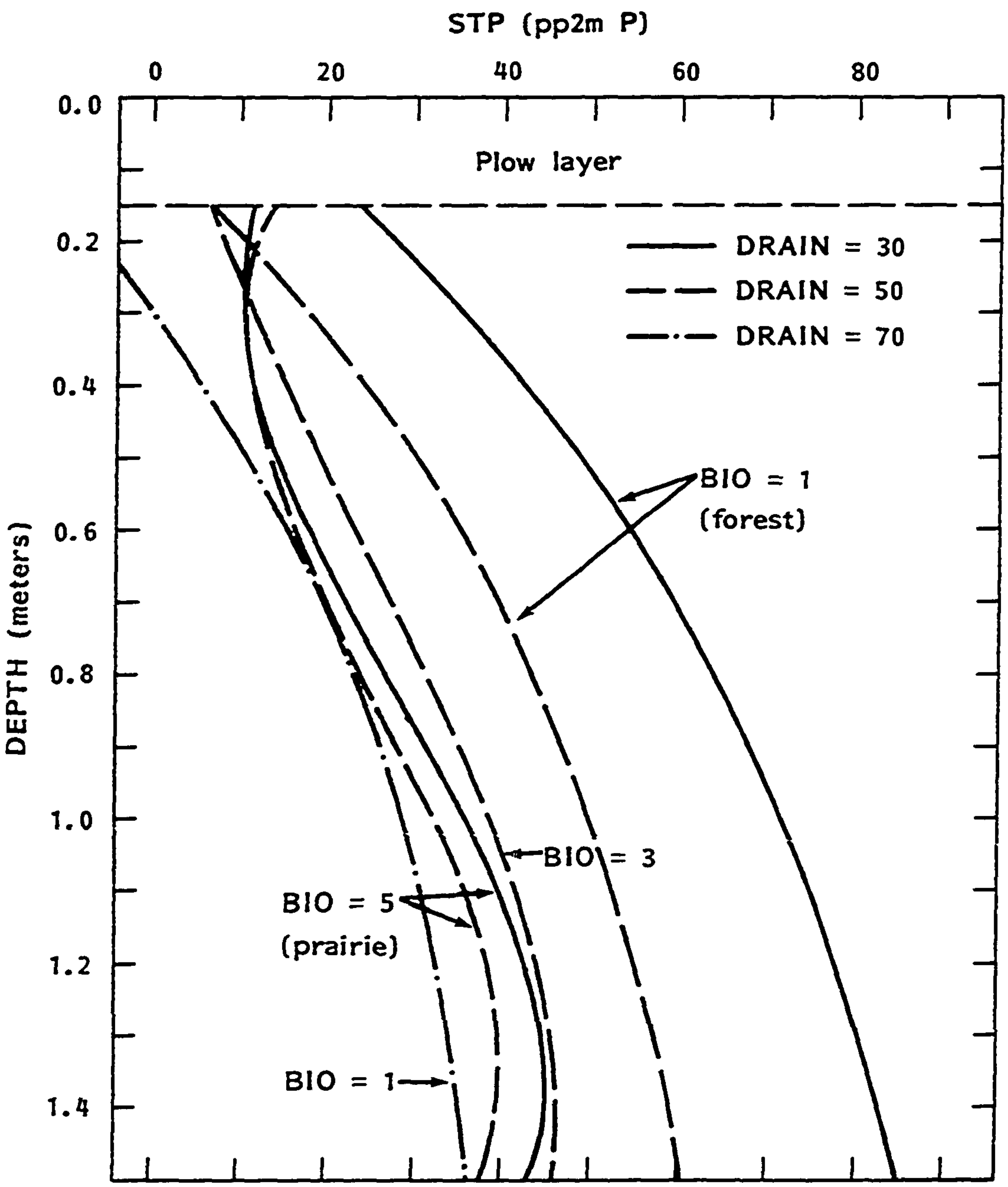

Figure 22. Predicted STP distributions with depth at various drainage class (DRAIN) and biosequence (BIO) levels

PH - 0.0492 STK + 0.0666 BD + 2.80 PEDISED + 4.73 ALLUV-T + 5.38 EOLIAN + 0.240 SLOPE + 0.0731 THAHOR + 0.225 DRAIN + 0.394 TEMP. Thus, the negative slope of STP on coded BIO varied in a cubic manner with depth because of the interactions with the cubic function of DEPTH, became more negative as STK1 increased, and became less negative as the levels of all other interacting variables increased because of their positive interactions with BIO.

The dominant effects of the BIO variable on predicted STP distributions were shown previously in Figures 16 (PH*BIO interaction), 20 (SLOPE*BIO interaction), and 22 (DRAIN*BIO interaction). The effects of the BIO, DEPTH, and TEMP interactions on predicted STP distributions are shown in Figure 23. The higher STP levels in the forest soils than in the prairie soils at all depths are shown in all of these figures. The STP distributions of the transition soils (BIO = 3) were between those of the forest and prairie soils but somewhat closer to those of the prairie than of the forest soils due to the curvilinear BIO effect on STP.

The STP distributions with DEPTH were sigmoid (cubic) in the prairie soils, slightly sigmoid to quadratic in the transition soils, and primarily quadratic in the forest soils. These various distributions were accounted for in the regression model by the three interactions between BIO and the cubic function of DEPTH.

All of the other interactions with BIO illustrated in Figures 16, 20, 22, and 23 were positive ones and thus showed similar patterns on STP distributions. The differences between STP levels at BIO = 1 and

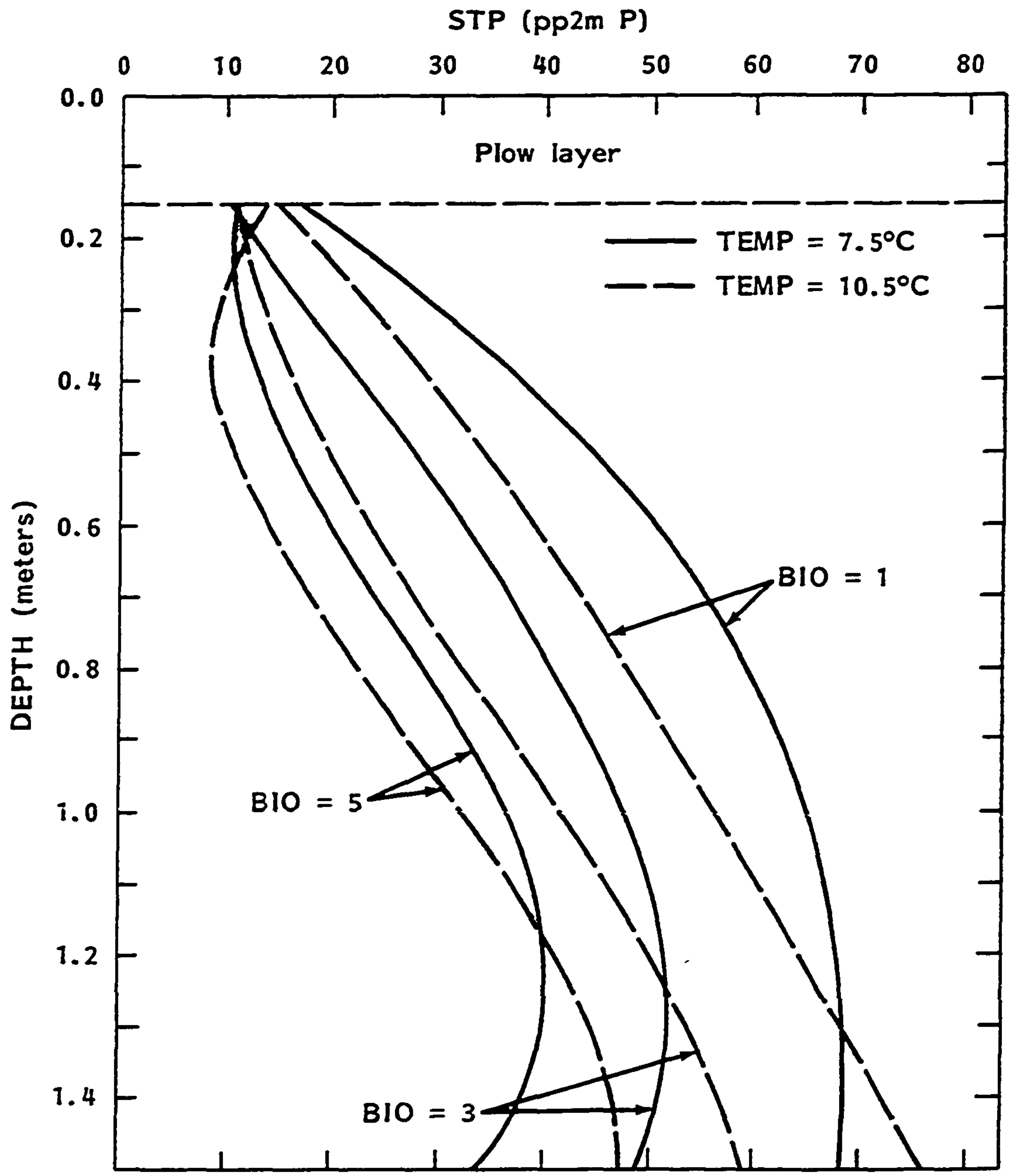

Figure 23. Predicted STP distributions with depth at various mean annual temperature (TEMP) and biosequence (BIO) levels

BIO = 5 decreased in all cases as the level of the interacting variables (PH, SLOPE, DRAIN, and TEMP) increased. The magnitudes of these differences, however, varied considerably depending on the degree of the interaction. These differences also varied between the upper and deeper layers of the profile.

DPHMIN The dSTP/dDPHMIN (Table 30) = 0.540 - 1.34 DEPTH + 2.49 $DEPTH^2$ - 1.19 $DEPTH^3$ + 0.00406 CLAY - 0.00448 BD + 0.176 ALLUV-L + 0.094 ALLUV-T - 0.00921 SLOPE - 0.00650 THAHOR. The slope of the linear STP response on DPHMIN varied in a cubic manner with DEPTH because of the three interactions between DPHMIN and cubic functions of DEPTH. These interactions affected the relationship between STP and DPHMIN similar to that shown for the quadratic effect of DPHMIN on STP in Figure 12. The positive slope of the linear STP response on DPHMIN increased as CLAY level increased and in the ALLUV-L and ALLUV-T parent materials and decreased as BD, SLOPE, and THAHOR levels increased.

The effects of the interactions between DPHMIN, DEPTH, and CLAY on predicted STP were shown previously in Figure 18. The differences in STP levels from DPHMIN = 30 to DPHMIN = 50 at most depths became greater as CLAY increased from 20 to 40; this effect showed the positive CLAY*DPHMIN interaction. The interactions between DPHMIN and the cubic function of DEPTH are not marked in this example for the prairie soil and at PH = 1.5 (pH = 6.0); they are shown at a constant CLAY level by the decreasing STP difference between DPHMIN levels in the upper part of the profile down to about 0.6 m deep, increasing STP difference to about 1.3 m deep, and then a decreasing STP difference below 1.3 m.

DCMAX In MODEL M-6 (Table 30), dSTP/dDCMAX = 0.0223 - 0.135 DEPTH + 0.164 $DEPTH^2$ + 0.00049 STK - 0.00187 CLAY - 0.111 ALLUV-T + 0.00191 DRAIN - 0.00434 PPT. Thus, the linear response of STP on DCMAX level varied in a quadratic manner because of the interactions with the quadratic function of DEPTH (as shown in Figure 11B), increased as STK and DRAIN levels increased, and decreased as CLAY and PPT levels increased and in the ALLUV-T parent material.

The effects of the interactions between DCMAX, DEPTH, and PPT on predicted STP levels are shown in Figure 24. At PPT = 73 cm (28.8 in.), a positive STP response to increasing DCMAX levels occurred only in the deeper subsoil; at PPT = 88 cm (34.7 in.), the STP responses to DCMAX levels were negative in the upper profile, became 0 at about 1.1 m deep, and then became positive below 1.1 m deep. These DCMAX effects at the two PPT levels were due to the DCMAX*PPT interaction.

PPT The dSTP/dPPT (Table 30) = 0.525 - 0.0343 PPT + 2.145 DEPTH - 1.200 $DEPTH^2$ - 0.275 PH + 0.00363 STK - 0.00434 DCMAX. The slopes of the curvilinear STP response on PPT varied in a quadratic manner because of the interactions with the quadratic function of DEPTH, became more positive as STK increased, and became less positive as PH and DCMAX levels increased.

The effects of the interactions between PPT, DEPTH, and PH on STP were shown previously in Figure 17 and between PPT, DEPTH, and DCMAX in Figure 24. The increase in STP with increased PPT level at most depths decreased as PH level increased from pH 5.5 to 6.5 because of the negative PH*PPT interaction (Figure 17). This relationship was reversed

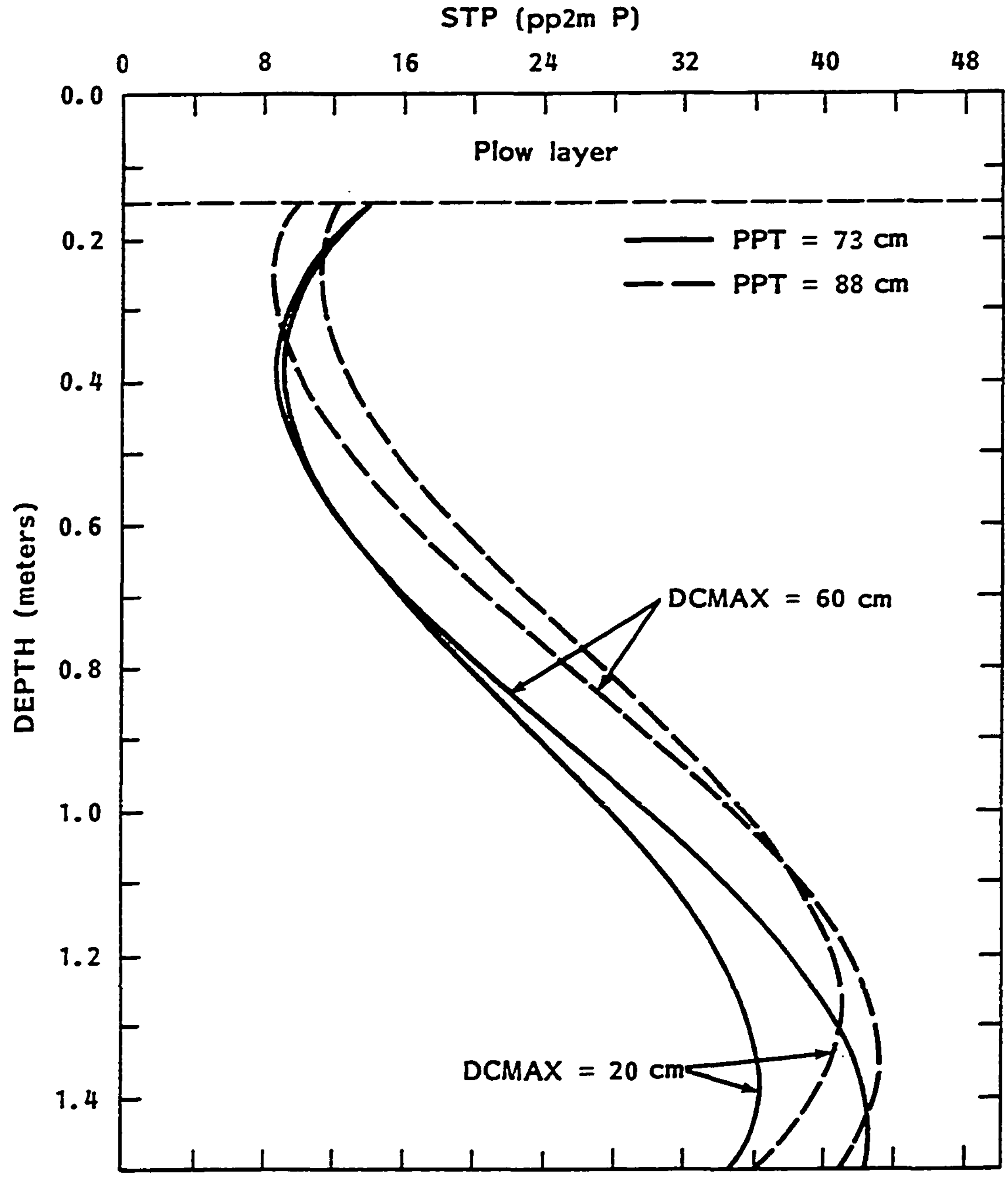

Figure 24. Predicted STP distributions with depth at various mean annual precipitation (PPT) and depth to maximum clay (DCMAX) levels

at pH 7.5 but few, if any, of the deep loess soils in the 88 cm PPT area of the state have a subsoil pH level of 7.5 for the constant values used for the interaction variables. In Figure 24, the STP levels increased at most depths as PPT increased from 73 to 83 cm. These differences were less as DCMAX increased from 20 to 60 cm deep due to the negative DCMAX*PPT interaction.

TEMP In MODEL M-6 (Table 30), the dSTP/dTEMP = -1.60 - 14.83 DEPTH + 10.49 $DEPTH^2$ + 0.851 PH - 0.0363 STK + 0.0386 BD + 0.0483 THAHOR + 0.394 BIO. The slopes of the linear response of STP on TEMP varied in a quadratic manner with depth because of the interactions with the quadratic function of DEPTH, became less negative or more positive as PH, BD, THAHOR, and BIO levels increased, and became more negative or less positive as STK level increased.

The effects of the interactions between TEMP, DEPTH, and THAHOR on predicted STP were shown in Figure 21. The effects between TEMP, DEPTH, and BIO on STP were shown in Figure 23. The STP levels at most depths except the lowest ones decreased as TEMP increased in both figures. The positive THAHOR*TEMP interaction in Figure 21 and the positive BIO*TEMP interaction in Figure 23 showed that the negative effect of TEMP became less negative as THAHOR and BIO levels, respectively, increased. The reversal of the TEMP effects on STP in the top part of the profile in the prairie soils and in the lowest layers in all soils showed the interactions between TEMP and the quadratic function of DEPTH. The effects of the increased rate of soil development due to increased TEMP shifted the STP distributions downward in all soils and was most noticeable in Figure 21. The depths in the lower profile associated with STPMAX increased as TEMP increased.

Summary of MODELS J to M series

The MODELS J to M series were used to develop the final prediction model of STP on selected variates from all groups of variables except the location variables. Interactions between variables other than the DEPTH variable were selected after examining all interactions tested in the previous study (Salih, 1979); 78 interactions out of 123 possible ones were randomly assigned to the MODELS J and K series (39 variates each, along with the base set of 57 variates from final MODEL G-10). After rigorous selection of interaction variates at the 1% level, the 18 and 22 most significant interactions of final MODELS J-9 and K-8, respectively, were combined with the base set of 57 variates from MODEL G-10 and tested in the MODEL L series. The R^2 of the final MODEL L-5 with 88 variates was 0.772 which was considerably higher than the R^2 of 0.673 of MODEL G-10.

For the final MODEL M series, 9 interaction variates which had been significant at the 1% to 5% level prior to deletion from the MODELS J and K series were retested along with the 88 variates from MODEL L-5. After stepwise, backward elimination of variates not significant at the 5% level, MODEL M-6 was selected as the final prediction model. It had 88 variates and an R^2 of 0.776.

The large number of significant interaction variates in final MODEL M-6 showed the complexity of the interrelationships among the variables on subsoil P distributions with depth. Fifteen DEPTH*X_i, 9 $DEPTH^2$*X_i, and 2 $DEPTH^3$*X_i interactions were retained in MODEL M-6. The BIO variable was involved in 13 interactions; this was expected because biosequence has a dominant effect on subsoil P levels. The numbers of interactions that the other variables were involved in were: DPHMIN had 9 interactions; PH and BD each had 8; CLAY, DCMAX, and TEMP had 7; DRAIN had 6; SLOPE, ALLUV-T, and PPT had 5; STK, ALLUV-L, and THAHOR had 4; PEDISED had 3; EOLIAN had 2; and COLLUV-L had 1 interaction.

From the regression coefficients of final prediction MODEL M-6, the effects of the variables and their interactions on STP (subsoil P) distributions with depth were examined and discussed using two methods. In the first method, the partial derivative of STP with respect to the X_i variable gave the slope of the STP response on X_i and its changes due to one or more interactions with DEPTH and the positive or negative interactions with other variables. The level of X_i associated with STPMAX or STPMIN and the ΔSTP for given changes in the X_i variable were computed to show some of the variable effects on STP. In the second method, a computer program was used to compute predicted STP values for DEPTH and various combinations of two other variables from a simplified regression equation obtained by holding all other variables constant. These effects on STP distributions were illustrated with figures for all variables except STK and the parent material variables.

The dominant BIO variable had a negative, curvilinear effect on STP distributions (decreasing magnitude from forest to prairie) which was modified by interactions with the cubic function of DEPTH and many positive interactions with PH, BD, PEDISED, ALLUV-T, EOLIAN, SLOPE, THAHOR, DRAIN, and TEMP. The predicted STP distributions with DEPTH were sigmoid in the prairie soils, slightly sigmoid to quadratic in the transition soils, and primarily quadratic in the forest soils; these distributions were described by the three interactions between BIO and the cubic function of DEPTH. The positive interactions showed that the differences between STP levels in the forest and prairie soils decreased as the levels of the interacting variables increased.

The PH variable had a curvilinear effect on STP modified by interactions with the quadratic function of DEPTH, positive interactions with BD, ALLUV-L, BIO, and TEMP, and negative interactions with CLAY and PPT. The different PH effects on STP in the upper and deeper profile were described by the interactions between PH and the quadratic function of DEPTH. The negative effect of PH on STP became less negative or more negative as the levels of variables having positive or negative interactions, respectively, with PH were increased.

The BD variable, which reflected primarily the effects of the till-derived soils and sandy terrace soils on STP distributions, had interactions with the quadratic function of DEPTH and six other variables. The positive interactions showed that the negative effects of BD on STP became less as PH, DRAIN, BIO, and TEMP levels increased; the negative ones showed that the negative effects became greater as CLAY and DPHMIN levels increased.

In studying the effects of both BD and PH on STP in MODEL M-6, the BD and PH levels were held constant throughout the profile although each has a distribution with depth. From the large numbers of predicted STP values for various increments of DEPTH and other interacting variables, the STP distributions were shown for joint effects of DEPTH and BD and of DEPTH and PH. These results showed that MODEL M-6 can predict STP distribution patterns from decreasing with depth to strongly sigmoid if appropriate levels of the variables with depth are used.

The curvilinear effect of the CLAY variable on STP also was modified by interactions with the quadratic function of DEPTH and mostly negative interactions with other variables. The negative interactions with PH, BD, ALLUV-T, and DCMAX showed that the effect of CLAY level on STP decreased and the CLAY level at STPMAX decreased as the level of each one increased.

The slopes of the linear STP response on coded DRAIN (from excessive to poor) became more negative with DEPTH, less negative as BD, THAHOR, BIO, and DCMAX levels increased, and generally positive in the ALLUV-L parent material. As drainage became poorer, predicted STP decreased markedly in the forest soils but much less so in the prairie soils, for example.

The effects of the other horizon and profile variables (STK, SLOPE, THAHOR, DPHMIN, DCMAX, PPT, and TEMP) on predicted STP levels were not as marked as those discussed; however, the effects of all were modified by several significant interactions. All of the parent material variables had negative interactions with DEPTH on predicted STP level plus one to four other interactions. The negative effect of each parent material (except ALLUV-L) on STP level compared to the average of all others (dominantly deep loess) became greater with increasing depth in the profile.

Multiple Regressions of STP on All Except Horizon Variables, Interaction MODELS N and P Series

In the previous study (Salih, 1979), deletion of the horizon variables had reduced the R^2 for predicting STP2 (subsoil P in the 76–107 cm layer) from about 0.79 in the all-variable final model to about 0.76. This loss was not excessive considering the time and cost of determining or estimating the horizon variables.

Two final prediction models without the horizon variables were selected in this study, one without the GHP (genetic horizon) variable (MODEL N series) and the other with the GHP variable (MODEL P series). The GHP variable, which is intercorrelated with several other variables including depth, was tested and deleted from the all-variable models because it had little effect on R^2. In the quadratic MODEL E series without the horizon variables, deletion of the GHP variable, however, reduced the R^2 about 0.03 (Table 15).

The STP models without the horizon variables (PH, STK, CLAY, BD, and GHP) should be useful for studying the relationships between STP and the DEPTH, parent material, profile, and climatic variables. One disadvantage of the models with the horizon variables was that these variables were held constant at all depths to study their interactions with DEPTH and other variables on STP. This unrealistic assumption was noted and discussed for the final MODEL M-6. The effects of the horizon variables on STP are joint effects with DEPTH because each one has its own depth distribution in the profile. For prediction of STP from MODEL M-6, these joint effects of the horizon variables and depth will be accounted for if the appropriate values of the horizon variables are used in the prediction equation.

The advantage of the models without the horizon variables for studying the effects of the other variables on STP distributions is that the joint effects of the horizon variables and depth are partially accounted for by their intercorrelations with depth and other variables. All of their effects were not accounted for, however, as shown by the decrease in R^2 from 0.613 to 0.578 (with GHP) and from 0.604 to 0.546 (without GHP) caused by deletion of the horizon variables in the final models of the MODELS C and E series (Tables 12 and 15).

For estimating subsoil P distributions of mapping units (all slope and erosion classes, for example) without profile descriptions, the final model of the MODEL N series (without the GHP variable) can be used. For estimating STP distributions of mapping units that have profile descriptions, the final model of the MODEL P series (with the GHP variable) will give more precise estimates.

For the MODEL N series, the significant variates in final MODEL H-8 were used as the base set of variates. The interactions between the other variables, except those with DEPTH which were included in the base set, were added and the final model selected.

For the MODEL P series, the 75 significant variates in final MODEL N-12 were used as the base set of variates. To these, the linear and squared GHP variates, all interaction variates between GHP and the other variables, and two variates for retesting (PEDISED*THAHOR and SLOPE* DPHMIN) were added and the final model selected.

Model selection

In the initial models, all variates listed in Table 32 were included in MODEL N-1 and all variates listed in Table 33 were included in MODEL P-1. The model selection steps are listed in Table 34 for both the MODELS N and P series.

Initially, the $DEPTH^3$ variate and the higher-order DEPTH interactions were deleted in MODELS N-2 and P-2 to determine their importance for estimating STP. The reductions in R^2 were about 0.02 and 0.015, respectively.

In MODELS N-3 to N-12 and MODELS P-2 to P-11, the nonsignificant variates were deleted stepwise (Table 34), following the variate selection steps described previously. The final models were MODEL N-12 with 75 variates and an R^2 of 0.719 and MODEL P-11 with 81 variates and an R^2 of 0.745.

The deletion of the horizon variables in the absence and presence of the GHP variable and its associated interactions reduced the R^2 from 0.776 in MODEL M-6 (final all-variable model) to 0.719 in MODEL N-12 and to 0.745 in MODEL P-11, respectively (Tables 28 and 34). Thus, these results were similar to those in the final quadratic models of the MODELS C and E series (Tables 12 and 15). These results lead to the conclusion that deletion of the horizon variables causes some loss in precision for predicting STP and deletion of horizon variables and the GHP variable causes a moderate loss in precision.

Table 32. Variates included in the multiple regressions of STP on all variables except the genetic horizon (GHP) and horizon variables, MODEL N series

X_i	Variate	X_i	Variate	X_i	Variate
2	STP (dep. var.)	35	DEPTH*EOLIAN	67	ALLUV-L*DPHMIN
3	PEDISED	36	*SLOPE	69	*DCMAX
4	TILL	37	*THAHOR	70	*PPI
5	COLLUV-L	38	*DRAIN	71	ALLUV-T*BIO
6	ALLUV-L	39	*BIO	72	*DPHMIN
7	ALLUV-T	40	*PHMIN	73	*DCMAX
8	EOLIAN	41	*DPHMIN	74	*PPT
		42	*DCMAX	75	EOLIAN*BIO
9	SLOPE	43	*PPT		
10	THAHOR	44	*TEMP	76	SLOPE*THAHOR
11	DRAIN			77	*DRAIN
12	BIO	45	DEPTH^2*SLOPE	78	*BIO
13	PHMIN	46	*BIO	79	*PHMIN
14	DPHMIN	47	*DPHMIN	80	*DPHMIN
15	DCMAX	48	*DCMAX		
16	PPT			81	THAHOR*DRAIN
17	TEMP	49	DEPTH^3*BIO	82	*BIO
		50	*DPHMIN	83	*PHMIN
18	DEPTH			84	*DCMAX
19	DEPTH^2	51	PEDISED*THAHOR	85	*PPT
20	DEPTH^3	52	*DRAIN	86	*TEMP
		53	*BIO		
21	SLOPE^2	54	*PHMIN	87	DRAIN*BIO
22	THAHOR^2	55	*DPHMIN	88	*DPHMIN
23	DRAIN^2	56	*PPT	89	*DCMAX
24	BIO^2	57	*TEMP	90	*PPT
25	PHMIN^2			91	*TEMP
26	DPHMIN^2	58	TILL*THAHOR	92	BIO*PHMIN
27	DCMAX^2	59	*DRAIN	93	*DPHMIN
28	PPT^2	60	*BIO	94	*TEMP
29	TEMP^2	61	*PHMIN		
		62	*DPHMIN	95	PHMIN*DPHMIN
30	DEPTH*PEDISED	63	*PPT	96	*PPT
31	*TILL	64	*TEMP	97	DPHMIN*DCMAX
32	*COLLUV-L			98	DCMAX*PPT
33	*ALLUV-L	65	ALLUV-L*DRAIN	99	*TEMP
34	*ALLUV-T	66	*PHMIN	100	PPT*TEMP

Table 33. Variates included in the multiple regressions of STP on all variables except the horizon variables, MODEL P series

X_i	Variate	X_i	Variate	X_i	Variate
2	GHP	36	DEPTH*THAHOR	70	PEDISED*BIO
3	STP (dep. var.)	37	*DRAIN	71	*PHMIN
4	PEDISED	38	*BIO		
5	TILL	39	*PHMIN	72	TILL*DRAIN
6	COLLUV-L	40	*DPHMIN	73	*BIO
7	ALLUV-L	41	*DCMAX	74	*PHMIN
8	ALLUV-T	42	*PPT	75	*DPHMIN
9	EOLIAN	43	*TEMP	76	ALLUV-L*DRAIN
10	SLOPE	44	$DEPTH^2$*GHP	77	ALLUV-T*BIO
11	THAHOR	45	*SLOPE	78	*DPHMIN
12	DRAIN	46	*BIO	79	*DCMAX
13	BIO	47	*DPHMIN	80	*PPT
14	PHMIN	48	*DCMAX	81	EOLIAN*BIO
15	DPHMIN				
16	DCMAX	49	$DEPTH^3$*GHP	82	SLOPE*THAHOR
17	PPT	50	*BIO	83	*DRAIN
18	TEMP	51	*DPHMIN	84	*BIO
				85	*PHMIN
19	DEPTH	52	GHP*PEDISED	86	*DPHMIN
20	$DEPTH^2$	53	*TILL		
21	$DEPTH^3$	54	*COLLUV-L	87	THAHOR*DRAIN
		55	*ALLUV-L	88	*BIO
22	GHP^2	56	*ALLUV-T	89	*DCMAX
23	$DRAIN^2$	57	*EOLIAN	90	*TEMP
24	$PHMIN^2$				
25	$DPHMIN^2$	58	*SLOPE	91	DRAIN*BIO
26	PPT^2	59	*THAHOR	92	*DPHMIN
27	$TEMP^2$	60	*DRAIN	93	*DCMAX
		61	*BIO	94	*TEMP
28	DEPTH*GHP	62	*PHMIN		
29	*PEDISED	63	*DPHMIN	95	BIO*PHMIN
30	*TILL	64	*DCMAX	96	*TEMP
31	*COLLUV-L	65	*PPT		
32	*ALLUV-L	66	*TEMP	97	PHMIN*PPT
33	*ALLUV-T			98	DPHMIN*DCMAX
34	*EOLIAN	67	PEDISED*THAHOR	99	DCMAX*PPT
35	*SLOPE	68	*DRAIN	100	PPT*TEMP

Table 34. Model selection steps, MODELS N and P series

Model no.	No. of X variates	Model selection steps	R^2
N- 1	97	Initial model; all variables listed in Table 32	.7207
2	90	Deleted highly significant $DEPTH^3$ and all $DEPTH^2$ and $DEPTH^3$ interactions from MODEL N-1	.7013
3 to 6	91 to 84	Deleted nonsignificant BIO^2, PEDISED*DPHMIN, TILL*THAHOR, TILL*PPT, ALLUV-L*PHMIN, ALLUV-L*DPHMIN, ALLUV-L*DCMAX, THAHOR*PHMIN, THAHOR*PPT, DRAIN*PPT, BIO*DPHMIN, PHMIN*DPHMIN, and DCMAX*TEMP stepwise from MODEL N-1	.7206 to .7199
7 to 9	81 to 78	Deleted ns $SLOPE^2$, $THAHOR^2$, $DCMAX^2$, PEDISED*PPT, PEDISED*TEMP, and ALLUV-L*PPT stepwise from MODEL N-6	.7194 to .7190
10 to 12	77 to 75	Deleted ns PEDISED*THAHOR, TILL*TEMP, and SLOPE*DPHMIN stepwise from MODEL N-9; MODEL N-12 was the final model	.7187 to .7185
P- 1	97	Initial model; all variates listed in Table 33	.7461
2	88	Deleted $DEPTH^3$ and all $DEPTH^2$ and $DEPTH^3$ interactions from MODEL P-1	.7316
3 to 8	94 to 86	Deleted nonsignificant DEPTH*PHMIN, DEPTH*PPT, $DEPTH^2$*DCMAX, $DEPTH^3$*GHP, GHP*COLLUV-L, GHP*ALLUV-L, GHP*DRAIN, GHP*PPT, GHP*TEMP, PEDISED*PHMIN, and PHMIN*PPT stepwise from MODEL P-1	.7461 to .7454
9 to 11	83 to 81	Deleted ns $DEPTH^2$*GHP, PEDISED*THAHOR, PEDISED*DRAIN, TILL*PHMIN, and THAHOR*DRAIN stepwise from MODEL P-8; MODEL P-11 was the final model	.7449 to .7445

Effect of the selected variates on STP

The regression statistics for final MODELS N-12 and P-11 are given in Table 35. All squared and interaction variates were significant at the 5% or 1% level except the DEPTH*DPHMIN variate in MODEL P-11. Presence of the GHP variable in MODEL P-11 added linear and squared variates of GHP, the DEPTH*GHP interactions, and 10 interactions with other variables, listed in order in Table 35. In MODEL N-12, 15 DEPTH*X_i and 4 DEPTH^2*X_i interactions occurred; addition of GHP to MODEL P-11 reduced the number to 14 DEPTH*X_i and 3 DEPTH^2*X_i interactions. These interactions are listed in order in Table 35.

The interactions between the variables other than DEPTH are summarized in Tables 36 and 37 for MODELS N-12 and P-11, respectively. The interactions are listed twice, once with each interacting variable. Most variables had interactions with the same variables in both final models except for the additional interaction with GHP in MODEL P-11. In some cases, an interaction not quite significant at the 5% level was deleted in one model but this interaction was retained in the other one because it was significant at the 5% level. Addition of the GHP variable affected the number of interactions with only the PHMIN and PPT variables because of intercorrelation among these variables. The interactions between PHMIN and DEPTH, PEDISED, TILL, and PPT in MODEL N-12 were not significant in MODEL P-11; those between PPT and DEPTH, PHMIN, and DCMAX in MODEL N-12 were deleted from MODEL P-11.

Most of the regression coefficients of the corresponding variates in MODELS N-12 and P-11 were similar; most of the coefficients of the

Table 35. Regression statistics of STP on selected variates, final MODELS N-12 (all except GHP and horizon variables) and P-11 (all except horizon variables)

Variate[a]	MODEL N-12		MODEL P-11	
	X_i	b_i	X_i	b_i
GHP (35; 0-80)	--	--	2	0.4603**
PEDISED (--; 0-1)	3	- 32.12**	4	- 23.01**
TILL (--; 0-1)	4	- 35.03**	5	- 26.67**
COLLUV-L (--; 0-1)	5	2.19	6	3.30++
ALLUV-L (--; 0-1)	6	- 7.89**	7	- 7.74**
ALLUV-T (--; 0-1)	7	- 27.18**	8	- 24.52**
EOLIAN (--; 0-1)	8	- 38.81**	9	- 38.38**
SLOPE (4; 0-20)	9	- 2.363**	10	- 2.360**
THAHOR (34; 0-109)	10	- 0.8054**	11	- 0.5947**
DRAIN (44; 10-85)	11	- 1.729**	12	- 1.791**
BIO (4.6; 1-5)	12	- 13.84**	13	- 15.18**
PHMIN (1.7; 0.4-3.6)	13	- 9.460**	14	- 11.82**
DPHMIN (32; 15-94)	14	0.2952*	15	0.1976+
DCMAX (52; 18-122)	15	0.09382*	16	- 0.009751
PPT (17; 0-26)	16	1.168**	17	0.6554**
TEMP (2; 0.2-3.8)	17	- 3.209**	18	- 1.511+
DEPTH (0.7; 0.15-1.4)	18	262.01**	19	194.54**
$DEPTH^2$	19	-320.85**	20	-258.35**
$DEPTH^3$	20	120.08**	21	100.67**
GHP^2	--	--	22	- 0.002084**
$DRAIN^2$	23	0.001816*	23	0.001909**
$PHMIN^2$	25	- 0.8454**	24	- 0.5935*
$DPHMIN^2$	26	- 0.001415*	25	- 0.001263*
PPT^2	28	- 0.03064**	26	- 0.02142**
$TEMP^2$	29	- 0.9989**	27	- 1.198**
DEPTH*GHP	--	--	28	0.06751*
*PEDISED	30	- 13.16**	29	- 7.10*
*TILL	31	- 15.59**	30	- 5.60**
*COLLUV-L	32	- 13.36**	31	- 14.74**
*ALLUV-L	33	- 9.50**	32	- 6.27**
*ALLUV-T	34	- 16.14**	33	- 10.67**
*EOLIAN	35	- 27.78**	34	- 12.51**

[a]Rounded means and ranges from Table 4 are shown in parentheses.

Table 35. (Continued)

Variate	MODEL N-12		MODEL P-11	
	X_i	b_i	X_i	b_i
DEPTH*SLOPE	36	1.751**	35	1.735**
*THAHOR	37	0.1340**	36	0.09924**
*DRAIN	38	- 0.2194**	37	- 0.2015**
*BIO	39	- 52.82**	38	- 44.09**
*PHMIN	40	- 2.852**	—	—
*DPHMIN	41	- 1.262*	40	- 0.7767+
*DCMAX	42	- 0.1939*	41	0.06465**
*PPT	43	0.2548**	—	—
*TEMP	44	3.184**	43	2.634**
$DEPTH^2$*SLOPE	45	- 1.523**	45	- 1.467**
*BIO	46	62.15**	46	54.24**
*DPHMIN	47	2.770**	47	1.658*
*DCMAX	48	0.2252**	—	—
$DEPTH^3$*BIO	49	- 22.22**	50	- 19.23**
*DPHMIN	50	- 1.412**	51	- 0.9049*
GHP*PEDISED	—	—	52	- 0.1466**
*TILL	—	—	53	- 0.1864**
*ALLUV-T	—	—	56	- 0.1388**
*EOLIAN	—	—	57	- 0.2587**
*SLOPE	—	—	58	0.005565**
*THAHOR	—	—	59	0.001784**
*BIO	—	—	61	- 0.05232**
*PHMIN	—	—	62	- 0.07687**
*DPHMIN	—	—	63	0.003461**
*DCMAX	—	—	64	0.000734*
PEDISED*DRAIN	52	0.06773*	—	—
*BIO	53	5.822**	70	5.512**
*PHMIN	54	1.664*	—	—
TILL*DRAIN	59	0.1391**	72	0.09283**
*BIO	60	5.762**	73	5.889**
*PHMIN	61	3.501**	—	—
*DPHMIN	62	- 0.1175**	75	- 0.1355**
ALLUV-L*DRAIN	65	0.3297**	76	0.3042**

Table 35. (Continued)

Variate	MODEL N-12		MODEL P-11	
	X_i	b_i	X_i	b_i
ALLUV-T*BIO	71	7.789**	77	7.902**
*DPHMIN	72	-0.08790*	78	-0.1211**
*DCMAX	73	-0.08942**	79	-0.1294**
*PPT	74	0.2657**	80	0.3836**
EOLIAN*BIO	75	8.861**	81	9.425**
SLOPE*THAHOR	76	-0.01242**	82	-0.01559**
*DRAIN	77	0.02134**	83	0.02021**
*BIO	78	0.4112**	84	0.4059**
*PHMIN	79	-0.2374**	85	-0.1482**
*DPHMIN	—	—	86	-0.007259*
THAHOR*DRAIN	81	0.002171**	—	—
*BIO	82	0.1142**	88	0.08065**
*DCMAX	84	0.000722*	89	0.001340**
*TEMP	86	0.07239**	90	0.08108**
DRAIN*BIO	87	0.2668**	91	0.3061**
*DPHMIN	88	0.002832**	92	0.003051**
*DCMAX	89	0.001421**	93	0.001484**
*TEMP	91	-0.04399**	94	-0.06268**
BIO*PHMIN	92	2.867**	95	3.139**
*TEMP	94	0.5235**	96	0.4079**
PHMIN*PPT	96	-0.1348**	—	—
DPHMIN*DCMAX	97	-0.001455**	98	-0.001633**
DCMAX*PPT	98	-0.006239**	99	-0.005281**
PPT*TEMP	100	0.1306**	100	0.1616**
Intercept	—	82.50**	—	88.31**
R^2	—	0.718**	—	0.744**

Table 36. Summary of the variable effects in final MODEL N-12, all variables except GHP and horizon variables

Variable[a]	t-values of Linear	t-values of Squared	Interacting variables with listed variable and their signs[b]
PEDISED	-12.5**	--	-DEPTH, +DRAIN, +BIO, +PHMIN
TILL	-10.8**	--	-DEPTH, +DRAIN, +BIO, +PHMIN, -DPHMIN
COLLUV-L	1.1	--	-DEPTH
ALLUV-L	- 3.6**	--	-DEPTH, +DRAIN
ALLUV-T	- 5.0**	--	-DEPTH, +BIO, -DPHMIN, -DCMAX, +PPT
EOLIAN	- 9.4++	--	-DEPTH, +BIO
SLOPE	- 7.1**	ns	+DEPTH, -DEPTH^2, -THAHOR, +DRAIN, +BIO, -PHMIN
THAHOR	- 8.5**	ns	+DEPTH, -SLOPE, +DRAIN, +BIO, +DCMAX, +TEMP
DRAIN	-12.5**	2.4*	-DEPTH, +PEDISED, +TILL, +ALLUV-L, +SLOPE, +THAHOR, +BIO, +DPHMIN, +DCMAX, -TEMP
BIO	- 7.8**	ns	-DEPTH, +DEPTH^2, -DEPTH^3, +PEDISED, +TILL, +ALLUV-T, +EOLIAN, +SLOPE, +THAHOR, +DRAIN, +PHMIN, +TEMP
PHMIN	- 4.0**	-2.9**	-DEPTH, +PEDISED, +TILL, -SLOPE, +BIO, -PPT
DPHMIN	2.4*	-2.2*	-DEPTH, +DEPTH^2, -DEPTH^3, -TILL, -ALLUV-T, +DRAIN, -DCMAX
DCMAX	2.1*	ns	-DEPTH, +DEPTH^2, -ALLUV-T, +THAHOR, +DRAIN, -DPHMIN, -PPT
PPT	6.3**	-7.1**	+DEPTH, +ALLUV-T, -PHMIN, -DCMAX, +TEMP
TEMP	- 2.9**	-4.2**	+DEPTH, +THAHOR, -DRAIN, +BIO, +PPT

[a]Interactions of DEPTH, DEPTH^2, and DEPTH^3 are listed in order in Table 35.

[b]Significance of interactions are given in Table 35.

Table 37. Summary of the variable effects in final MODEL P-11, all variables except horizon variables

Variable[a]	t-values of Linear	t-values of Squared	Interacting variables with listed variable and their signs[b]
GHP	6.5**	-5.7**	+DEPTH, -PEDISED, -TILL, -ALLUV-T, -EOLIAN, +SLOPE, +THAHOR, -BIO, -PHMIN, +DPHMIN, +DCMAX
PEDISED	-10.0**	--	-DEPTH, -GHP, +BIO
TILL	- 8.5**	--	-DEPTH, -GHP, +DRAIN, +BIO, -DPHMIN
COLLUV-L	1.8*	--	-DEPTH
ALLUV-L	- 3.8**	--	-DEPTH, +DRAIN
ALLUV-T	- 4.8**	--	-DEPTH, -GHP, +BIO, -DPHMIN, -DCMAX, +PPT
EOLIAN	- 9.8**	--	-DEPTH, -GHP, +BIO
SLOPE	- 6.1**	ns	+DEPTH, -DEPTH^2, +GHP, -THAHOR, +DRAIN, +BIO, -PHMIN, -DPHMIN
THAHOR	- 6.5**	ns	+DEPTH, +GHP, -SLOPE, +BIO, +DCMAX, +TEMP
DRAIN	-13.5**	2.7**	-DEPTH, +TILL, +ALLUV-L, +SLOPE, +BIO, +DPHMIN, +DCMAX, -TEMP
BIO	- 9.0**	ns	-DEPTH, +DEPTH^2, -DEPTH^3, -GHP, +PEDISED, +TILL, +ALLUV-T, +EOLIAN, +SLOPE, +THAHOR, +DRAIN, +PHMIN, +TEMP
PHMIN	- 6.3**	-2.2*	-GHP, -SLOPE, +BIO
DPHMIN	1.6+	-2.0*	-DEPTH, +DEPTH^2, -DEPTH^3, +GHP, -TILL, -ALLUV-T, -SLOPE, +DRAIN, -DCMAX
DCMAX	- 0.29	ns	+DEPTH, +GHP, -ALLUV-T, +THAHOR, +DRAIN, -DPHMIN, -PPT
PPT	7.3**	-6.0**	+ALLUV-T, -DCMAX, +TEMP
TEMP	- 1.5+	-5.4**	+DEPTH, +THAHOR, -DRAIN, +BIO, +PPT

[a]Interactions of DEPTH, DEPTH^2, and DEPTH^3 are listed in order in Table 35.

[b]Significances of interactions are given in Table 35.

linear variates were also similar although these commonly vary with the number of interactions involving the variable. The presence of the GHP variable decreased the coefficients of the interactions between DEPTH and the parent material variables with which GHP had interactions. The difference between the DEPTH*DCMAX coefficients in the two models was due to deletion of the $DEPTH^2$*DCMAX interaction in MODEL P-11.

Deletion of the horizon variables in MODEL N-12 altered the number of interactions that some of the variables had in final all-variable MODEL M-6. Most variables, however, had about the same number of interactions in the two models, as shown in Tables 30 and 31 for MODEL M-6 and Tables 35 and 36 for MODEL N-12. The PHMIN variable was included in MODEL N-12; because of its high correlation with PH of 0.79, it accounted for much of the effect of PH in MODEL M-6. The TILL parent material variable in MODEL N-12 which was highly correlated with BD (r = 0.72) had many of the interactions that BD had in MODEL M-6. The effect of the CLAY variable in MODEL M-6 was accounted for in part by its correlation of 0.55 with DRAIN in MODEL N-12.

The numbers of the DEPTH*X_i interactions were the same in MODELS M-6 and N-12 (Tables 30 and 35); three with horizon variables were deleted in MODEL N-12 but the DEPTH*TILL, DEPTH*PHMIN, and DEPTH*THAHOR interactions were added. The interactions between $DEPTH^2$ and the horizon variables were not accounted for by interactions with their correlated variables in MODEL N-12; in addition, the two interactions between $DEPTH^2$ and the PPT and TEMP variables were not significant in MODEL N-12. The $DEPTH^3$*BIO and $DEPTH^3$*DPHMIN were significant in both models.

The number of interactions with DRAIN increased to 10 in MODEL N-12 compared to 6 in MODEL M-6 (Tables 31 and 36). The PEDISED, ALLUV-T, SLOPE, THAHOR, DCMAX, PPT, and TEMP variables were involved in 1 or 2 more interactions with variables other than horizon variables in MODEL N-12 than in MODEL M-6. The ALLUV-L and DPHMIN variables were involved in one less interaction in MODEL N-12 than in MODEL M-6.

Many of the regression coefficients of corresponding variates in MODELS M-6 and N-12 varied considerably (Tables 30 and 35); this would be expected because of the different mix of the variables, squared variates, and interactions in the two models. Most of the coefficients of the parent material variates were more negative or more positive in MODEL N-12 than in MODEL M-6; thus, these variables would have larger effects on STP than they had in MODEL M-6. However, most of the coefficients for the interaction variates between DEPTH and the profile variables and between the profile variables were similar in both models.

Because of time limitation, the interpretation of the effects of the variables on STP in these models without the horizon variables will not be investigated as was done for MODEL M-6. However, these effects need to be investigated. The deletion of the horizon variables, most of which had many interactions with DEPTH and other variables, may change somewhat the effects of the profile, parent material, and climatic variables on STP distributions. As discussed in the introduction to this section, an advantage of the MODELS N and P series is that the effects of variables other than horizon variables can be studied without having the horizon variables fixed at a constant level throughout the profile. In these models, the joint effects of the horizon variables and DEPTH are indirectly, but not entirely, accounted for by their intercorrelations with DEPTH and the other variables.

The major objective for deriving the final MODELS N-12 and P-11 was for predicting STP distributions of many soil mapping units in Iowa from their parent material, soil profile characteristics, and climatic factors related to location in the state. If profile descriptions are available, MODEL P-11 will give more precision for predicting the STP distributions than MODEL N-12.

Summary of MODELS N and P series

Two series of regression models were used to develop the final STP prediction models without the horizon variables: the MODEL N series without the GHP (coded genetic horizon) variable and the MODEL P series with the GHP variable and its interactions with other variables.

The interactions between all variables, except those with the DEPTH variable which were included in the MODEL H series, were added to the 48 variates in final MODEL H-8 for the MODEL N series. The GHP variable (linear, squared, and interaction variates), the 75 significant variates in final MODEL N-12, and two interaction variates to be retested were included in the MODEL P series.

The final prediction models selected were MODEL N-12 with 75 variates and MODEL P-11 with 81 variates. Deletion of the horizon variables (PH, STK, CLAY, and BD) in the absence and presence of the GHP variable reduced the R^2 from 0.776 in all-variable MODEL M-6 to 0.719 in MODEL N-12 and to 0.745 in MODEL P-11.

Most variables had interactions with the same variables in both final MODELS N-12 and P-11 except for the additional interactions with GHP in the latter model. Addition of the GHP variable in MODEL P-11, however, resulted in deletion of 4 and 3 interactions with PHMIN and PPT, respectively, which had been significant in MODEL N-12. This was due to intercorrelations among these variables. Most of the regression coefficients of the corresponding variates, including the linear variates, were similar in both MODELS N-12 and P-11. The presence of the GHP variable, however, decreased the regression coefficients of the interactions between DEPTH and the parent material variables with which GHP had interactions.

Deletion of the horizon variables in MODEL N-12 changed the number of interactions that some of the variables had in the final all-variable MODEL M-6. Most, however, had about the same number of interactions in the two models. The number of interactions with DRAIN increased from 6 in MODEL M-6 to 10 in MODEL N-12. Several other variables were involved in 1 or 2 more interactions with variables other than the horizon variables in MODEL N-12 than in MODEL M-6.

Much of the effect of PH in MODEL M-6 was accounted for by the PHMIN variable added in MODEL N-12 because of their high correlation of 0.79. The effect of the BD variable in MODEL M-6 was accounted for by the addition of the highly correlated TILL variable ($r = 0.72$) in MODEL N-12. The additional interactions of the DRAIN variable in MODEL

N-12 accounted for part of the effects of the correlated CLAY variable ($r = 0.55$) in MODEL M-6.

Many of the regression coefficients of corresponding variates in MODELS M-6 and N-12 varied considerably; this would be expected because of the different mix of variates in the two models. Most coefficients of the parent material variates were larger in MODEL N-12 than in MODEL M-6; the parent material variables, in the absence of horizon variables, thus had larger effects on STP in MODEL N-12. However, most coefficients of the interaction variates involving the profile variables were similar in both models.

The effects of the variables on STP in the models without the horizon variables were not investigated as was done for MODEL M-6. This needs to be done so that the effects of the variables can be studied without having the horizon variables fixed at constant levels throughout the profile. In MODELS N-12 and P-11, the joint effects of the horizon variables and DEPTH are indirectly, but not entirely, accounted for by their intercorrelations with DEPTH and other variables.

The major objective for deriving the final MODELS N-12 and P-11 was for predicting STP distributions of the many soil mapping units in Iowa from the parent material, soil profile characteristics, and climatic factors related to location in the state. If profile descriptions are available, MODEL P-11 (with GHP variable) will predict STP more precisely than MODEL N-12.

SUMMARY AND CONCLUSIONS

In previous research, Salih (1979) studied the soil and location variables influencing the available phosphorus (P) in Iowa subsoils. These analyses were restricted to the fixed depths of 30-51 cm (12-20 in.) and 76-107 cm (30-42 in.) in the soil profile. This study was conducted to characterize the subsoil P distributions throughout the profiles mathematically as functions of soil, location, and climatic variables.

The major objectives of this research were: (1) to predict subsoil P levels at any depth in the soil profile from below the plow layer to 127 cm (50 in.) deep, utilizing depth, soil, location, and climatic variables; (2) to predict subsoil P levels at any depth in the soil profile without the soil horizon variables whose estimation or determination is time consuming and costly; (3) to compare the relative effects of the location variables and climatic variables for predicting subsoil P levels of Iowa soils; and (4) to describe the methodology for studying the simultaneous effects of two or three variables and their many interactions, including the higher-order interactions with depth, on subsoil P distributions in Iowa soil profiles.

The sources of the data used for this study were: (1) 663 soil profiles collected for a long-term soil productivity project under the supervision of Drs. Lloyd C. Dumenil and F. F. Riecken of the Agronomy Department; and (2) 33 profiles sampled by the Soil Survey Group of the Agronomy Department. The soil profiles from the soil productivity project were from 15 counties selected to represent the major soil association areas in the state. These counties were Adams, Bremer, Cass, Clay, Crawford, Fayette, Hamilton, Howard, Harrison, Keokuk, Linn, Lyon, Muscatine, Wayne, and Woodbury.

In each of the profiles, 4 to 10 horizons were described in detail and sampled. The number of horizons or observations used in this study were 3913. The horizons were tested for PH, and available N, P, and K by the Iowa State University Soil Testing Laboratory. The values for the horizon, parent material, location, and profile variables were determined from the soil profile descriptions or estimated by several procedures.

The soil horizon variables included depth in the profile (DEPTH), soil pH (PH), soil test P (STP), soil test K (STK), soil texture variables in percentages (SAND, SILT, and CLAY), organic carbon percentage (OC), and bulk density (BD).

The parent material variables included loess and deoxidized loess soil horizons (LOESS), soil horizons of pedisediment, sediments above till, and lacustrine material above till (PEDISED), till and paleosol horizons in the 127 cm (50 in.) profile (TILL), colluvium below loess soils (COLLUV-L), alluvium in loess areas (ALLUV-L), alluvium in till areas (ALLUV-T), and eolian LFS and FSL (EOLIAN).

Location variables included the legal township number to give the S-N direction (TWP) and the legal range number for E-W direction (RANGE). Climatic variables included mean annual temperature (TEMP), mean annual precipitation (PPT), and mean annual potential evapotranspiration (PE).

The profile variables included coded genetic horizon (GHP), percentage slope of the site (SLOPE), thickness of A horizon (THAHOR), coded erosion class (EROS), coded slope configuration of the site (SLCONF), minimum PH in the profile (PHMIN), depth to minimum pH (DPHMIN), coded natural internal drainage class (DRAIN), coded biosequence (BIO), coded depth to the top of the calcareous horizon (DCAL), maximum clay in the profile (CMAX), and depth to the midpoint of the maximum clay horizon (DCMAX).

The original data associated with each described soil horizon of the profile were punched on two cards. The data needed from the original data cards were then combined on a new data card; a program was written to transfer the data for the variables to the new card, one card for each horizon of each profile. In the same program of computing and transferring the data to new cards, all measurements of the variables were transformed to metric units. Also, the original 12 parent material listings were transformed to the 7 parent material groups listed (LOESS with all zeros plus six others which were coded 1 in their respective columns) to decrease the number of variables.

The results of this study were presented and discussed in six sections. In the first section, simple averages of minimum and maximum subsoil P, soil pH, and clay parameters of selected parent material, soil series, and mapping unit groups were computed. In the second section, results of the simple correlation analysis to detect the intercorrelations among the variables were presented.

The third section involved the multiple regression analysis of

STP on linear functions of the parent material variables, the cubic function of depth in the profile (DEPTH), and quadratic functions of all other variables. Also, the relative importance of the location and climatic variables and of the horizon and genetic horizon variables were tested in alternate models for predicting STP. In the fourth section, the interactions between the linear, quadratic, and cubic functions of DEPTH and all variables previously selected were tested in two series of models, with and without the horizon variables. The significant $DEPTH*X_i$, $DEPTH^2*X_i$, and $DEPTH^3*X_i$ interactions were discussed.

The fifth section involved testing the effects on STP of many interactions between the other variables in the presence of previously selected variates. The final all-variable prediction equation of STP on selected variates was presented and discussed. The sixth section involved selection of STP interaction models on all selected variables except the horizon variables. Final prediction models, without and with the genetic horizon variable, were presented and discussed.

Minimum and Maximum Subsoil P Levels of Selected Soils

To show the variations in subsoil P levels among soils, simple averages of minimum (STPMIN) and maximum (STPMAX) subsoil P levels were computed for various soils or groups of soils. The average depths to STPMAX (DPMAX) were also computed for the soil groups with sigmoid (S-shaped) P distributions. To characterize the soil profile development, average values for minimum pH in the profile (PHMIN), depth to minimum pH (DPHMIN), maximum percentage clay in the profile (CMAX), and depth to maximum clay (DCMAX) were also computed for each group. The subsoil P in the soil profiles showed two general distribution curves: (1) a sigmoid (S-shaped) curve in which the subsoil level was minimum immediately below the plow layer or decreased to a minimum in the upper part of the profile and then increased with depth to a maximum in the deeper part of the profile; and (2) a decreasing curve in which the STPMAX level occurred immediately below the plow layer and decreased with depth.

The Marshall, Sharpsburg, and Macksburg soils had the highest STPMAX values of the deep loess, prairie soils in western Iowa. Many of Monona, Galva, and Moody soils had both types of distribution curves; the decreasing curves occurred if depths to carbonates were shallow. In southern Iowa, the Seymour and Edina soils had lower STPMIN and STPMAX levels than Marshall and Sharpsburg soils farther west. The forested, deep loess soils of eastern Iowa had much higher STPMIN and STPMAX levels than the prairie soils. The transition soils had intermediate levels. The moderately eroded soils generally had less STPMAX than slightly eroded ones; the PHMIN values were greater and the DPHMIN and DCMAX values were less in the moderately eroded than in the slightly eroded soils.

The till-derived soils had much less subsoil P than the loess-derived soils except those that had decreasing subsoil P levels due to higher pH levels in the deeper subsoils. About 70% in the Iowa erosional surface and Kansan till areas and 95% in the Cary till area had decreasing P distribution curves and very low levels of subsoil P.

The colluvial soils below the loess soils had lower STPMAX levels than the associated upland soils. About 80% of the alluvial soils in the Missouri River bottomland area showed a decreasing subsoil P distribution but the alluvial soils in the local bottomlands of western Iowa had higher subsoil P levels than the adjacent upland soils. The alluvial soils in the loess area of eastern Iowa had about the same subsoil P as the upland prairie soils. The alluvial soils in the till area had less subsoil P than alluvial soils in the loess areas but more than the associated upland soils.

In eastern Iowa, the eolian sands had higher subsoil P levels than the associated till soils. The shallow loess over till soils had less subsoil P than the associated deep loess soils.

Correlation Analysis

In the initial analysis, the correlation coefficients between soil, location, and climatic variables were computed and used as guidance to select the variables for multiple regression analysis. Because PE (potential evapotranspiration) was highly correlated with TWP and TEMP ($r = -0.96$ and 0.99, respectively), it was excluded from further analysis.

Most of the soil pH-related variables (GHP, PH, DCAL, PHMIN, DPHMIN, and RANGE), texture-related variables (SAND, SILT, CLAY, BD, TILL, DRAIN, and CMAX), organic matter-related variables (OC, SLOPE, SLCONF, EROS, and THAHOR), and location and climatic variables (TWP, RANGE, PPT, and TEMP) were highly intercorrelated. Several variables were correlated greater than ± 0.70; the high intercorrelations complicated variable selection in the multiple regressions.

Multiple Regressions, MODELS A to F Series

Multiple regressions of STP (soil test P) were computed initially on quadratic functions of all variables except the linear functions of parent material variables (which were dummy or linear variables) and the cubic function of the DEPTH variable. The cubic function of DEPTH was included to explain the sigmoid distributions of STP in many Iowa soils.

Different regressions were selected for varying degrees of correlation between the variables, as follows: (1) high correlations disregarded (MODELS A and B series); and (2) no variables included which were correlated greater than ± 0.60 (MODELS C to F series).

The effects of the climatic variables (PPT and TEMP) and location variables (TWP and RANGE) on STP were compared in alternate models. The climatic variables were included in the MODELS A, C, and E series; location variables were tested in MODELS B, D, and F.

The horizon variables were deleted in MODELS E and F to test how well STP could be predicted without including the horizon variables. Also, additional models were computed in the MODELS C to F series to determine the importance of the GHP (genetic horizon) variable for predicting STP.

The final complete prediction MODEL A-8 (with climatic variables) and MODEL B-9 (with location variables), in which the high correlations between variables were disregarded, had R^2-values of 0.630 and 0.625, respectively. In the MODELS C and D series, the variables that were correlated greater than ± 0.60 were tested in alternate models; the one that gave the higher R^2 was retained and the other was deleted. The final MODELS C-17 and D-17, in which no variables were included that were correlated greater than ± 0.60, had R^2-values of 0.613 and 0.608, respectively. Thus, deletion of highly correlated variables reduced the R^2 by 0.017. Deletion of the GHP variable (intercorrelated with several other variables) further reduced the R^2-values of the final MODELS C-23 and D-22 to 0.605 and 0.601, respectively.

The relationships between the variables and STP under conditions of minimum distortion of the regression coefficients due to intercorrelations among variables were of more interest in this study than maximum precision in predicting STP (highest R^2). Therefore, the significant variates in final MODEL C-23 were included in the initial interaction models.

In all models with climatic variables (MODELS A, C, and E), the R^2-values were slightly higher than those with the location variables (MODELS B, D, and F). Because the climatic variables of PPT and TEMP were slightly better for predicting STP than the location variables of TWP and RANGE, only the climatic variables were included in the interaction models.

Deletion of the horizon variables in the final MODEL E-12 reduced the R^2 to 0.578, about 0.035 less than the R^2 of the comparable MODEL C-17. This agreed with the previous study by Salih (1979). Deletion of the GHP variable in final MODEL E-15 reduced the R^2 to 0.546, a decrease of 0.032 from that of MODEL E-12. The GHP variable had a slight effect on STP in the MODEL C series and was deleted from the interaction models. However, it had much more effect on STP in the absence of the horizon variables (primarily the PH variable) and was included in one of the final interaction models.

The following variables had significant effects on STP in MODEL C-23: linear functions of STK, PEDISED, COLLUV-L, ALLUV-L, EOLIAN, and DPHMIN; quadratic functions of PH, CLAY, BD, THAHOR, DRAIN, BIO, PPT, and TEMP; and the cubic function of DEPTH. In final MODEL E-12 (horizon variables deleted), the following had significant effects on STP: linear functions of all parent material variables and quadratic functions of DEPTH, GHP, SLOPE, THAHOR, DRAIN, BIO, PHMIN, DPHMIN, DCMAX, PPT, and TEMP. The effect of each variable on STP in the final models in the different series had the same trend although the magnitudes of several varied because of intercorrelations.

Multiple Regressions, MODELS G and H Series

Because of wide variations in distributions of soil test P (STP) in Iowa subsoils with profile depth, ranging from marked sigmoid to decreasing patterns, many interactions between the linear, quadratic, and cubic functions of depth with the other variables were tested and selected to improve the prediction model.

For these and subsequent all-variable models, the location and the GHP variables were deleted. For the MODEL G series, the significant variates in MODEL C-23 were included as the base set plus the ALLUV-T, SLOPE, and DCMAX variables which were added for further testing. For the MODEL H series (horizon variables deleted), the significant variates in final MODEL E-15 were included as the base set and only $DEPTH^2$ and $DEPTH^3$ variates were added. To the base set of variates, all $DEPTH*X_i$ and $DEPTH^2*X_i$ and most $DEPTH^3*X_i$ interactions were added and tested for significance. In these and all subsequent models, the unit of the DEPTH variable was transformed from cm to meters.

To select the significant DEPTH interactions, the nonsignificant $DEPTH^3*X_i$ variates were deleted first, then the nonsignificant $DEPTH^2*X_i$ interactions were deleted next if the $DEPTH^3*X_i$ interactions were deleted previously, and then nonsignificant $DEPTH*X_i$ interactions were deleted if the $DEPTH^2*X_i$ interactions were deleted previously. If the higher-order DEPTH interaction with another variable was significant, the lower-order interaction was retained, regardless of its significance.

Addition of the ALLUV-T, SLOPE, and DCMAX variables and all of the significant interactions with DEPTH, $DEPTH^2$, and $DEPTH^3$ increased the R^2 of final MODEL G-10 with 57 variates to 0.673 from the R^2 of 0.605 in MODEL C-23. Addition of $DEPTH^2$, $DEPTH^3$, and all significant DEPTH, $DEPTH^2$, and $DEPTH^3$ interactions increased the R^2 of final MODEL H-8 with 48 variates to 0.640 from the R^2 of 0.546 in MODEL E-15.

In MODEL G-10, 2 of 14 $DEPTH^3*X_i$ interactions tested, 9 of 17 $DEPTH^2*X_i$, and 16 of 17 $DEPTH*X_i$ interactions had significant effects on STP, mostly at the 1% level. In MODEL H-8 (horizon variables deleted), 2 of 13 $DEPTH^3*X_i$, 4 of 15 $DEPTH^2*X_i$, and all 15 $DEPTH*X_i$ interactions tested were significant, mostly at the 1% level.

The effects of the other X_i variables on STP modified by one or more of the DEPTH*X_i, DEPTH^2*X_i, and DEPTH^3*X_i interactions were illustrated using partial derivatives of STP with respect to X_i or by computing the ΔSTP values at selected levels of the X_i variable and DEPTH. If a linear effect of X_i was modified by (1) the DEPTH*X_i interaction, or (2) the DEPTH*X_i and DEPTH^2*X_i interactions, the partial derivative of STP with respect to X_i (slope of the linear STP response on X_i) varied linearly or curvilinearly (in a quadratic manner), respectively, with increasing DEPTH.

If the X_i variable had a quadratic effect on STP modified by (1) the DEPTH*X_i interaction, (2) the DEPTH*X_i and DEPTH^2*X_i interactions, or (3) the linear, quadratic, and cubic interactions of DEPTH and X_i, both the magnitudes of the quadratic responses of STP on X_i and changes in the X_i associated with STPMIN or STPMAX varied in a linear, quadratic, or cubic manner, respectively, with increasing DEPTH.

Because the DEPTH variable had a cubic effect on STP modified by many interactions with other variables, the partial derivative of STP with respect to DEPTH had many terms. For example, dSTP/dDEPTH in MODEL H-8 included 3 terms for the cubic function of DEPTH, 15 terms for the DEPTH*X_i, 4 terms for the DEPTH^2*X_i, and 2 terms for the DEPTH^3*X_i interactions. The effects of 1 or 2 variables on the slopes of the STP response on DEPTH in the partial derivative can be determined by setting all other variables at constant levels and using the simplified partial derivative to determine the effects of the selected variables on the STP response to DEPTH.

Another method to study the effect of the cubic function of DEPTH on STP level, modified by one or more interactions with another variable, is to simplify the regression equation by substituting constant values for all other variables, multiplying them by their appropriate regression coefficients, and collecting terms. The simplified regression equation at fixed levels of other variables contains the cubic function of DEPTH, the linear or quadratic function of the interacting variable, and all interactions between the two.

The effects of DEPTH and an interacting X_i variable with 1, 2, or 3 interactions between DEPTH and X_i on STP were illustrated, using simplified regression equations. The effects of DEPTH on STP modified by (1) the linear, (2) the linear and quadratic, or (3) the linear, quadratic, and cubic DEPTH interactions with X_i were, respectively, as follows: (1) the DEPTH*X_i interaction modified the initial slope of the STP response on DEPTH, the DEPTH values associated with both STPMIN and STPMAX, and magnitudes of STP levels with increasing DEPTH due to the influence of the interacting variable, but gave similar curvilinearity of the cubic function of STP on DEPTH at various X_i levels; (2) the DEPTH*X_i and $DEPTH^2$*X_i interactions had the same effects as in (1) except that the coefficient of the $DEPTH^2$ variate was changed as X_i varied, which varied the curvilinearity of the cubic function of STP on DEPTH and caused marked contrasts between STP differences in the upper and deeper profile; and (3) all three interactions with DEPTH caused marked changes in the distributions of STP with DEPTH because the coefficient of the $DEPTH^3$ variate also varied with level of X_i. For example, in the presence of all three interactions between DEPTH and BIO, the prairie soil had a typical cubic (sigmoid) STP distribution with DEPTH, the forest-prairie soil had higher STP levels and a quadratic distribution with DEPTH, but the forest soil had even higher STP levels with a rapidly increasing STP level in the upper subsoil but a nearly constant STP level between 0.9 to 1.4 m deep, a STP distribution similar to an exponential response curve.

Multiple Regressions, MODELS J to M Series

The MODELS J to M series were used to develop the final prediction model of STP on selected variates from all groups of variables except the location variables. Interactions between variables other than the DEPTH variable were selected after examining all interactions tested in the previous study (Salih, 1979); 78 interactions out of 123 possible ones were randomly assigned to the MODELS J and K series (39 variates each, along with the base set of 57 variates from final MODEL G-10). After rigorous selection of interaction variates at the 1% level, the 18 and 22 most significant interactions of final MODELS J-9 and K-8, respectively, were combined with the base set of 57 variates from MODEL G-10 and tested in the MODEL L series. The R^2 of the final MODEL L-5 with 88 variates was 0.772 which was considerably higher than the R^2 of 0.673 of MODEL G-10.

For the final MODEL M series, 9 interaction variates which had been significant at the 1% to 5% level prior to deletion from the MODELS J and K series were retested along with the 88 variates from MODEL L-5. After stepwise, backward elimination of variates not significant at the 5% level, MODEL M-6 was selected as the final prediction model. It had 88 variates and an R^2 of 0.776.

The large number of significant interaction variates in final MODEL M-6 showed the complexity of the interrelationships among the variables on subsoil P distributions with depth. Fifteen DEPTH*X_i, 9 DEPTH^2*X_i, and 2 DEPTH^3*X_i interactions were retained in MODEL M-6. The BIO variable was involved in 13 interactions; this was expected because biosequence has a dominant effect on subsoil P levels. The numbers of interactions that the other variables were involved in were: DPHMIN had 9 interactions; PH and BD each had 8; CLAY, DCMAX, and TEMP had 7; DRAIN had 6; SLOPE, ALLUV-T, and PPT had 5; STK, ALLUV-L, and THAHOR had 4; PEDISED had 3; EOLIAN had 2; and COLLUV-L had 1 interaction.

From the regression coefficients of final prediction MODEL M-6, the effects of the variables and their interactions on STP (subsoil P) distributions with depth were examined and discussed using two methods. In the first method, the partial derivative of STP with respect to the X_i variable gave the slope of the STP response on X_i and its changes due to one or more interactions with DEPTH and the positive or negative interactions with other variables. The level of X_i associated with STPMAX or STPMIN and the ΔSTP for given changes in the X_i variable were computed to show some of the variable effects on STP. In the second method, a computer program was used to compute predicted STP values for DEPTH and various combinations of two other variables from a simplified regression equation obtained by holding other variables constant. These effects on STP distributions were illustrated with figures for all variables except STK and the parent material variables.

The dominant BIO variable had a negative, curvilinear effect on STP distributions (decreasing magnitude from forest to prairie) which was modified by interactions with the cubic function of DEPTH and many positive interactions with PH, BD, PEDISED, ALLUV-T, EOLIAN, SLOPE, THAHOR, DRAIN, and TEMP. The predicted STP distributions with DEPTH were sigmoid in the prairie soils, slightly sigmoid to quadratic in the transition soils, and primarily quadratic in the forest soils; these distributions were described by the three interactions between BIO and the cubic function of DEPTH. The positive interactions showed that the differences between STP levels in the forest and prairie soils decreased as the levels of the interacting variables increased.

The PH variable had a curvilinear effect on STP modified by interactions with the quadratic function of DEPTH, positive interactions with BD, ALLUV-L, BIO, and TEMP, and negative interactions with CLAY and PPT. The different PH effects on STP in the upper and deeper profile were described by the interactions between PH and the quadratic function of DEPTH. The negative effect of PH or STP became less negative or more negative as the levels of variables having positive or negative interactions, respectively, with PH were increased.

The BD variable, which reflected primarily the effects of the till-derived soils and sandy terrace soils on STP distributions, had interactions with the quadratic function of DEPTH and six other variables.

The positive interactions showed that the negative effects of BD on STP became less as PH, DRAIN, BIO, and TEMP levels increased; the negative ones showed that the negative effects became greater as CLAY and DPHMIN levels increased.

In studying the effects of both BD and PH on STP in MODEL M-6, the BD and PH levels were held constant throughout the profile although each has a distribution with depth. From the large numbers of predicted STP values for various increments of DEPTH and other interacting variables, the STP distributions were shown for joint effects of DEPTH and BD and of DEPTH and PH. These results showed that MODEL M-6 can predict STP distribution patterns from decreasing with depth to strongly sigmoid if appropriate levels of the horizon variables with depth are used.

The curvilinear effect of the CLAY variable on STP also was modified by interactions with the quadratic function of DEPTH and mostly negative interactions with other variables. The negative interactions with PH, BD, ALLUV-T, and DCMAX showed that the effect of CLAY level on STP decreased and the CLAY level at STPMAX decreased as the level of each one increased.

The slopes of the linear STP response on coded DRAIN (from excessive to poor) became more negative with DEPTH, less negative as BD, THAHOR, BIO, and DCMAX levels increased, and generally positive in the ALLUV-L parent material. As drainage became poorer, predicted STP decreased markedly in the forest soils but much less so in the prairie soils, for example.

The effects of the other horizon and profile variables (STK, SLOPE, THAHOR, DPHMIN, DCMAX, PPT, and TEMP) on predicted STP levels were not as marked as those discussed; however, the effects of all were modified by several significant interactions. All of the parent material variables had negative interactions with DEPTH on predicted STP level plus one to four other interactions. The negative effect of each parent material (except ALLUV-L) on STP level compared to the average of all others (dominantly deep loess) became greater with increasing depth in the profile.

Multiple Regressions, MODELS N and P Series

Two series of regression models were used to develop the final STP prediction models without the horizon variables: the MODEL N series without the GHP (coded genetic horizon) variable and the MODEL P series with the GHP variable and its interactions with other variables.

The interactions between all variables, except those with the DEPTH variable which were included in the MODEL H series, were added to the 48 variates in final MODEL H-8 for the MODEL N series. The GHP variable (linear, squared, and interaction variates), the 75 significant variates in final MODEL N-12, and two interaction variates to be retested were included in the MODEL P series.

The final prediction models selected were MODEL N-12 with 75 variates and MODEL P-11 with 81 variates. Deletion of the horizon variables (PH, STK, CLAY, and BD) in the absence and presence of the GHP variable reduced the R^2 from 0.776 in all-variable MODEL M-6 to 0.719 in MODEL

N-12 and to 0.745 in MODEL P-11.

Most variables had interactions with the same variables in both final MODELS N-12 and P-11 except for the additional interactions with GHP in the latter model. Addition of the GHP variable in MODEL P-11, however, resulted in deletion of 4 and 3 interactions with PHMIN and PPT, respectively, which had been significant in MODEL N-12. This was due to intercorrelations among these variables. Most of the regression coefficients of the corresponding variates, including the linear variates, were similar in both MODELS N-12 and P-11. The presence of the GHP variable, however, decreased the regression coefficients of the interactions between DEPTH and the parent material variables with which GHP had interactions.

Deletion of the horizon variables in MODEL N-12 changed the number of interactions that some of the variables had in the final all-variable MODEL M-6. Most, however, had about the same number of interactions in the two models. The number of interactions with DRAIN increased from 6 in MODEL M-6 to 10 in MODEL N-12. Several other variables were involved in 1 or 2 more interactions with variables other than the horizon variables in MODEL N-12 than in MODEL M-6.

Much of the effect of PH in MODEL M-6 was accounted for by the PHMIN variable added in MODEL N-12 because of their high correlation of 0.79. The effect of the BD variable in MODEL M-6 was accounted for by addition of the highly correlated TILL variable (r = 0.72) in MODEL N-12. The additional interactions of the DRAIN variable in MODEL N-12 accounted for part of the effects of the correlated CLAY variable (r = 0.55) in MODEL M-6.

Many of the regression coefficients of corresponding variates in MODELS M-6 and N-12 varied considerably; this would be expected because of the different mix of variates in the two models. Most coefficients of the parent material variates were larger in MODEL N-12 than in MODEL M-6; the parent material variables, in the absence of horizon variables, thus had larger effects on STP in MODEL N-12. However, most coefficients of the interaction variates involving the profile variables were similar in both models.

The effects of the variables on STP in the models without the horizon variables were not investigated as was done for MODEL M-6. This needs to be done so that the effects of the variables can be studied without having the horizon variables fixed at constant levels throughout the profile. In MODELS N-12 and P-11, the joint effects of the horizon variables and DEPTH are indirectly, but not entirely, accounted for by their intercorrelations with DEPTH and other variables.

The major objective for deriving the final MODELS N-12 and P-11 was for predicting STP distributions of the many soil mapping units in Iowa from the parent material, soil profile characteristics, and climatic factors related to location in the state. If profile descriptions are available, MODEL P-11 (with GHP variable) will predict STP more precisely than MODEL N-12.

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APPENDIX

Table A1. Original data listing on computer card 0 for soil test, horizon, parent material, location, and profile variables used for regression analyses

Col. no.	Identification or variable
1	Card no. = 0
2-4	Profile number from 001 to 734
5-6	County number from 01 = Adair Co. to 99 = Wright Co.
7-8	Year (last 2 digits) that profile was sampled
9-10	Site number if Corn Yield Study profile, or identification number of Soil Survey profiles within the county
11-14	Soil mapping unit number (col. 11 indicates variant; 1010 and 2010 are Monona variants)
15-16	Thickness (inches) of successive genetic horizons sampled from the soil profile, starting with the plow layer
17-20	Depth (inches) to the mid-point of each horizon sampled (decimal punched)
21-22	Genetic horizon coded as follows, based on relative P availability (Birchett's data): C2ca = 00 B23 = 50 Ap = 10 (identification, only) B31 = 60 A1, A2, A3, or B1 = 20 B3 or B32 = 70 B21 = 30 B33 = 75 B2 or B22 = 40 C1 = 80
23-25	pH of the horizon (decimal punched)
26-28	Soil test P of the horizon (pp2m)
29-31	Soil test K of the horizon (pp2m); values greater than 999 recorded as 999
32-33	Percent sand of the horizon (nareast whole number)
34-35	Percent silt of the horizon (nearest whole number)
36-37	Percent clay of the horizon (nearest whole number)

Table A1. (Continued)

Col. no.	Identification or variable
38-40	Percent organic carbon to nearest tenth (decimal punched)
41-42	Bulk density, coded: (bulk density value - 1.00)*100
43-53	Parent material of each horizon (dummy variables--0 or 1 entries), as follows:

	Column no. 43 to 53
1. Loess	000 000 000 00
2. Deoxidized loess	100 000 000 00
3. Pedisediment	010 000 000 00
4. Sediments (above till)	001 000 000 00
5. Till	000 100 000 00
6. Paleosol	000 010 000 00
7. Lacustrine	000 001 000 00
8. Colluvium (below loess soils)	000 000 100 00
9. Colluvium (below till soils)	000 000 010 00
10. Alluvium (loess areas)	000 000 001 00
11. Alluvium (till areas)	000 000 000 10
12. Eolian	000 000 000 01

Col. no.	Identification or variable
54-56	Location in state--township no. = 065 to 100
57-59	Location in state--range no. (R7E = -06 to R1E = 000, R1W = 001 to R49W = 049)
60-61	Slope of site area (%)
63	Slope configuration, coded:

1 = strongly convex
2 = convex
3 = convex to straight
4 = straight (flat)
5 = straight to concave
6 = concave

Col. no.	Identification or variable
64	Erosion class, coded:

0 = + (deposition) or none (>12" A horizon)
1 = slight (7-12" A horizon)
2 = moderate (3-7" A horizon)
3 = severe (<3" A horizon)

Col. no.	Identification or variable
65-66	Thickness of A horizon (A1 + A2 + A3) in inches

Table A1. (Continued)

Col. no.	Identification or variable
67-68	Natural internal drainage class, coded: 10 = excessive 20 = excessive to well 30 = well 40 = moderately well 50 = somewhat poor 60 = somewhat poor to poor 70 = poor 80 = poor to very poor 90 = very poor
71	Biosequence, coded: 1 = forest 2 = forest-transition intergrade 3 = transition 4 = transition-prairie intergrade 5 = prairie
72-73	Depth to top of carbonate horizon (coded: 60"-depth; more than 60" = 0)

Table A2. Original data listing on computer card 1 for climatic and additional soil variables

Col. no.	Identification or variable
1	Card no. = 1
2-4	Profile number
6-9	Mean annual precipitation in inches (PPT)
11-14	Mean annual temperature in °F (TEMP)
16-19	Mean annual temperature in °C (TEMP)
21-24	Mean annual evapotranspiration (PE) in cm
26-28	Minimum pH in soil profile (PHMIN)
30-33	Depth to minimum pH in profile (DPHMIN) in inches
35-36	Maximum percent clay in profile (CMAX)
38-41	Depth to maximum percent clay in profile (DCMAX) in inches

Table A3. Instructions for programming the transforming and transferring of variables from the original data cards 0 and 1 to the new data card

Variable symbol	Instructions	Original card Card no.	Original card Col. no.	Column no. punched on new data card
--	Data of plow layer, first card of profile and with genetic horizon coded 10, are not used; if col. 21 = 1, do not transfer any data from this card	0	21	--
--	Profile number, transfer to new card		2-4	2-4
	Horizon variables			
DEPTH	Depth to midpoint of horizon; multiply by 2.54 and transfer nearest whole number		17-20	5-7
GHP	Transfer to new card; if pH in col. 23-25 >7.8, set GHP = 00 and transfer		21-22	8-9
GHK	Transfer to new card; if genetic horizon = 00, set = 80 and transfer		21-22	10-11
PH	Subtract 4.5 and transfer to new card		23-25	12-14
STP	Transfer to new card		26-28	15-17
STK	Transfer to new card		29-31	18-20
SAND	Transfer to new card		32-33	21-22
SILT	Transfer to new card		34-35	23-24
CLAY	Transfer to new card		36-37	25-26
OC	Transfer to new card		38-40	27-29
BD	Transfer to new card		41-42	30-31

Table A3. (Continued)

Variable symbol	Instructions	Original card: Card no.	Original card: Col. no.	Column no. punched on new data card
	Parent material variables grouped and transferred, or reclassified according to following instructions, using columns 43-53 on original data card and columns 32-37 of new card			
LOESS	If 0 occurs in each of col. 43-53 (oxidized loess) or 1 occurs in col. 43 (deoxidized loess), punch 0's in col. 32-37	0	43-53	32-37
PEDISED	If 1 occurs in col. 44 (pedised.), col. 45 (sed./till), or col. 48 (lacustrine), punch 1 in col. 32 and 0's in col. 33-37		44,45,48	32
TILL	If 1 occurs in col. 46 (till) or col. 47 (paleosol), punch 1 in col. 33 and 0's in col. 32 and 34-37		46,47	33
COLLUV-L	If 1 occurs in col. 49 (colluv. below loess), punch 1 in col. 34 and 0's in 32-33 and 35-37	0	49	34
ALLUV-L	If 1 occurs in col. 51 (alluvium in loess areas), punch 1 in col. 35 and 0's in 32-34 and 36-37		51	35
ALLUV-T	If 1 occurs in col. 52 (alluvium in till areas), punch 1 in col. 36 and 0's in 32-35 and 37		52	36
EOLIAN	If 1 occurs in col. 53 (eolian sand), punch 1 in col. 37 and 0's in col. 32-36		53	37
	Location and profile variables transferred to new data card			
TWP	Subtract 65 and transfer to new card	0	54-56	38-39
RANGE	Transfer to new card		57-59	40-42
SLOPE	Transfer to new card		60-61	43-44

Table A3. (Continued)

Variable symbol	Instructions	Original card: Card no.	Original card: Col. no.	Column no. punched on new data card
SLCONF	Transfer to new card		63	45
EROS	Transfer to new card		64	46
THAHOR	Multiply by 2.54, round to nearest whole number, and transfer		65-66	47-49
DRAIN	Transfer to new card		67-68	50-51
BIO	Transfer to new card		71	52
DCAL	Multiply by 2.54, round to nearest whole number, and transfer		72-73	53-55
	Climatic and some soil variables, transferred from card 1 (1 in col. 1) to each new card having successive horizons for the same profile number (col. 2-4 on both card 0 and 1)			
PHMIN	Subtract 4.5, and transfer to new card	1	26-28	56-58
DPHMIN	Multiply by 2.54, round to nearest whole number, and transfer		30-33	59-61
CMAX	Transfer to new card		35-36	62-63
DCMAX	Multiply by 2.54, round to nearest whole number, and transfer		38-41	64-66
PPT	Multiply by 2.54, round to nearest tenth, subtract 63.0, and transfer		6-9	67-70
TEMP	Subtract 7.0, and transfer to new card		16-19	71-74
PE	Multiply by 2.54, round to nearest tenth, subtract 62.0, and transfer		21-24	75-78